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Keech et al.

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(54) **WAVEGUIDE-BASED OPTICAL SYSTEMS AND METHODS FOR AUGMENTED REALITY SYSTEMS**

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G02B 27/00 (2006.01)
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CPC ***G06K 9/00671*** (2013.01); ***G02B 6/12007*** (2013.01); ***G02B 6/1221*** (2013.01);
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CPC G06K 9/00671; G02B 27/0081; G02B 27/0172; G02B 6/12007; G02B 6/1221; G02B 2027/0178
See application file for complete search history.

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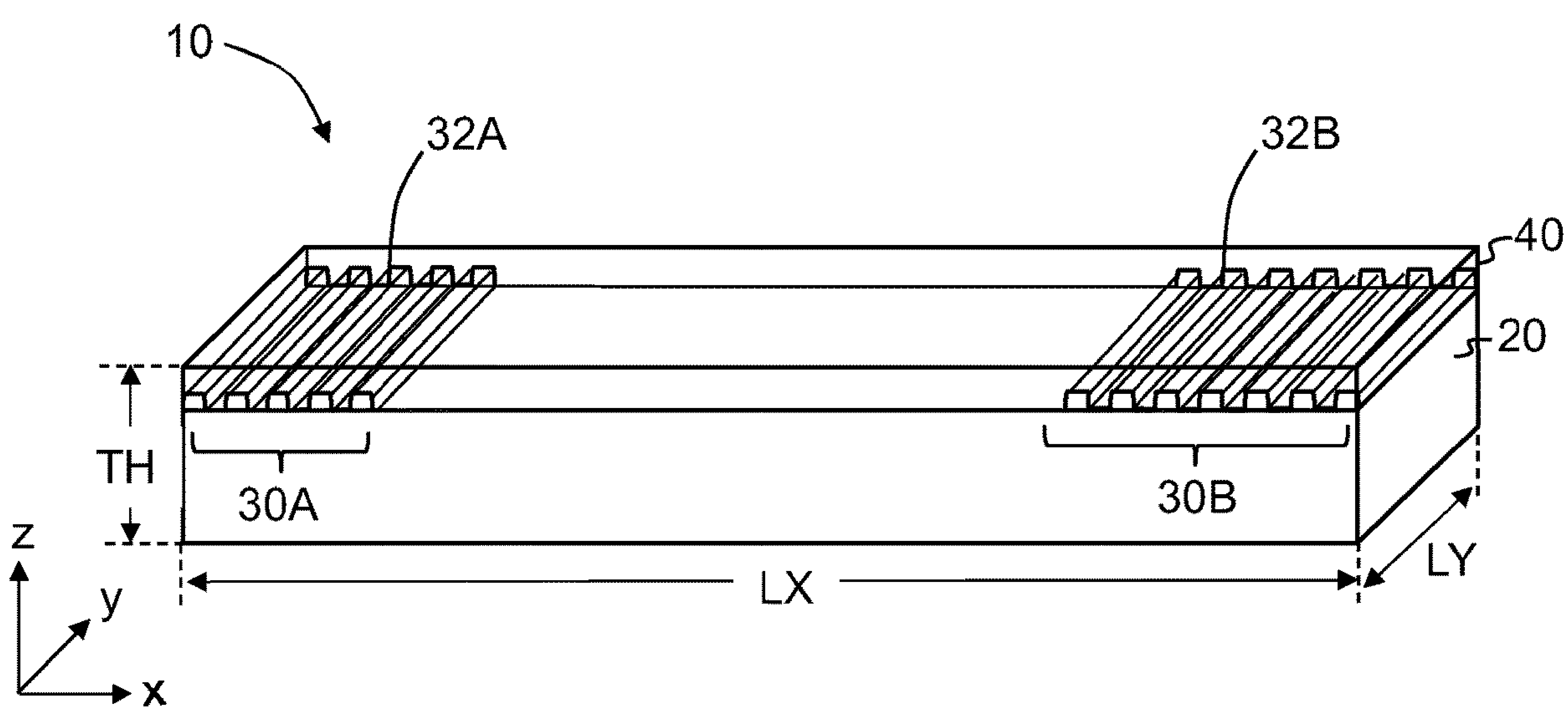
(57) **ABSTRACT**

An augmented reality optical system comprises a waveguide structure that includes a waveguide layer supported by a substrate. An input grating and an output grating reside within the waveguide layer and are laterally spaced apart. Input light from a display is made incident upon the input grating. The input light is coupled into the waveguide layer and travels therein as multiple guided modes to the output grating. The input and output gratings provide phase matching so that the guided modes are coupled out of the waveguide layer by the output grating continuously along the output grating to form output light. Meantime, light from a scene is transmitted perpendicularly through the output grating so that the output light and the light from the scene are combined by the eye of a user to form an augmented reality image.

30 Claims, 11 Drawing Sheets



(51) **Int. Cl.**
G02B 6/12 (2006.01)
G02B 6/122 (2006.01)
G02B 27/01 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 27/0081*** (2013.01); ***G02B 27/0172*** (2013.01); *G02B 2027/0178* (2013.01)

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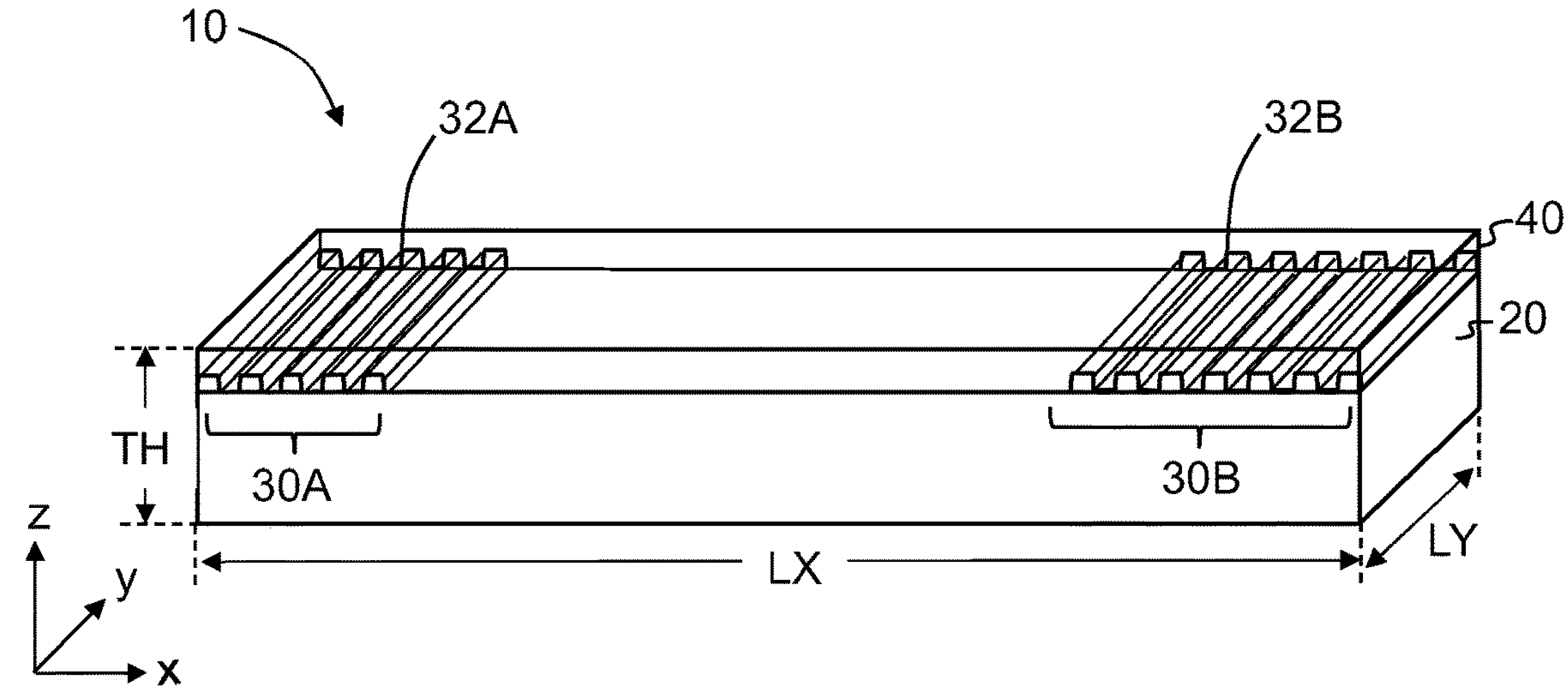

10
32A
32B
40
20
TH
30A
30B
z
y
x
LX
LY

FIG. 1

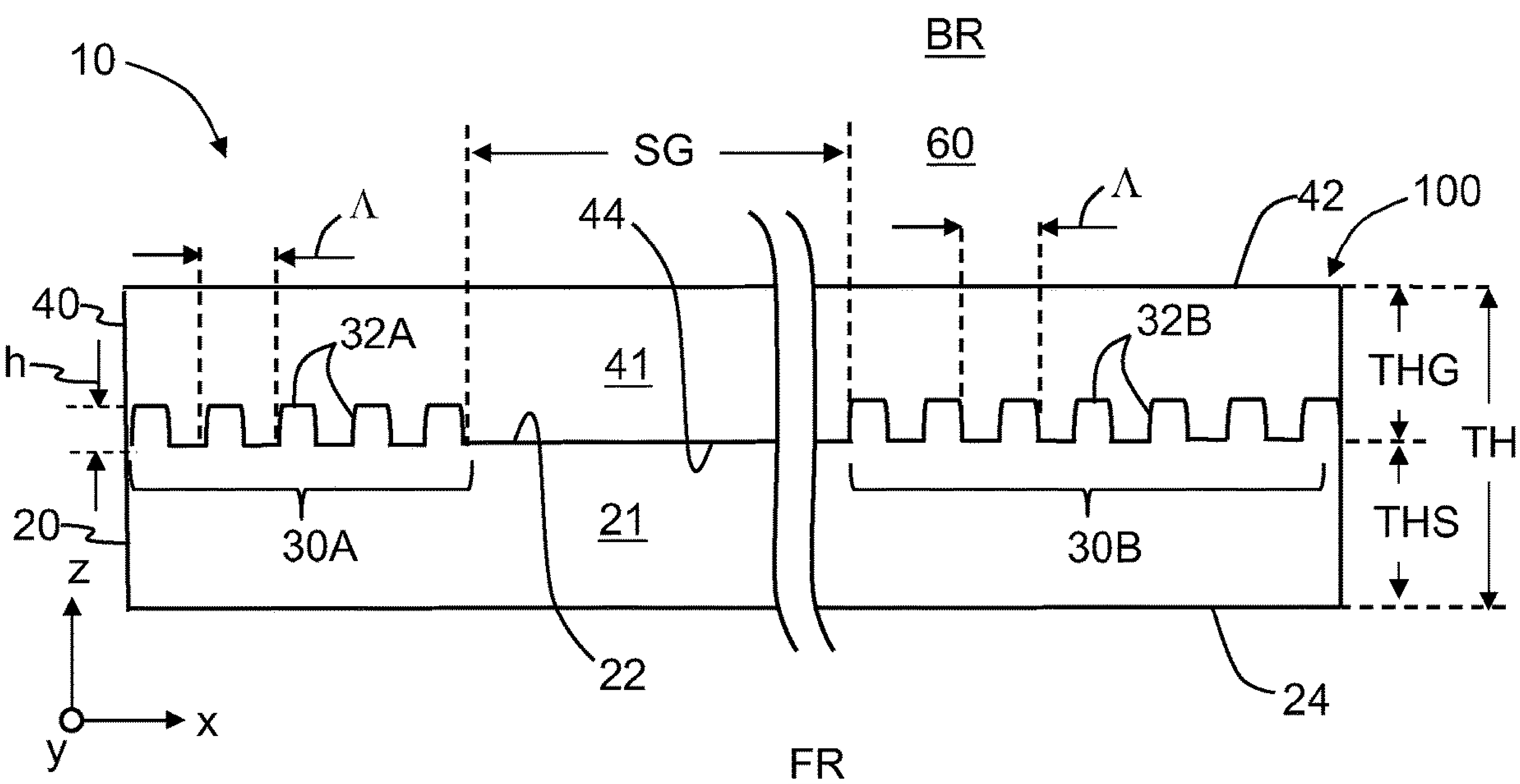

BR
10
SG
60
Λ
Λ
44
42
100
40
h
32A
41
32B
THG
TH
20
30A
21
30B
THS
z
22
24
x
y
FR

FIG. 2

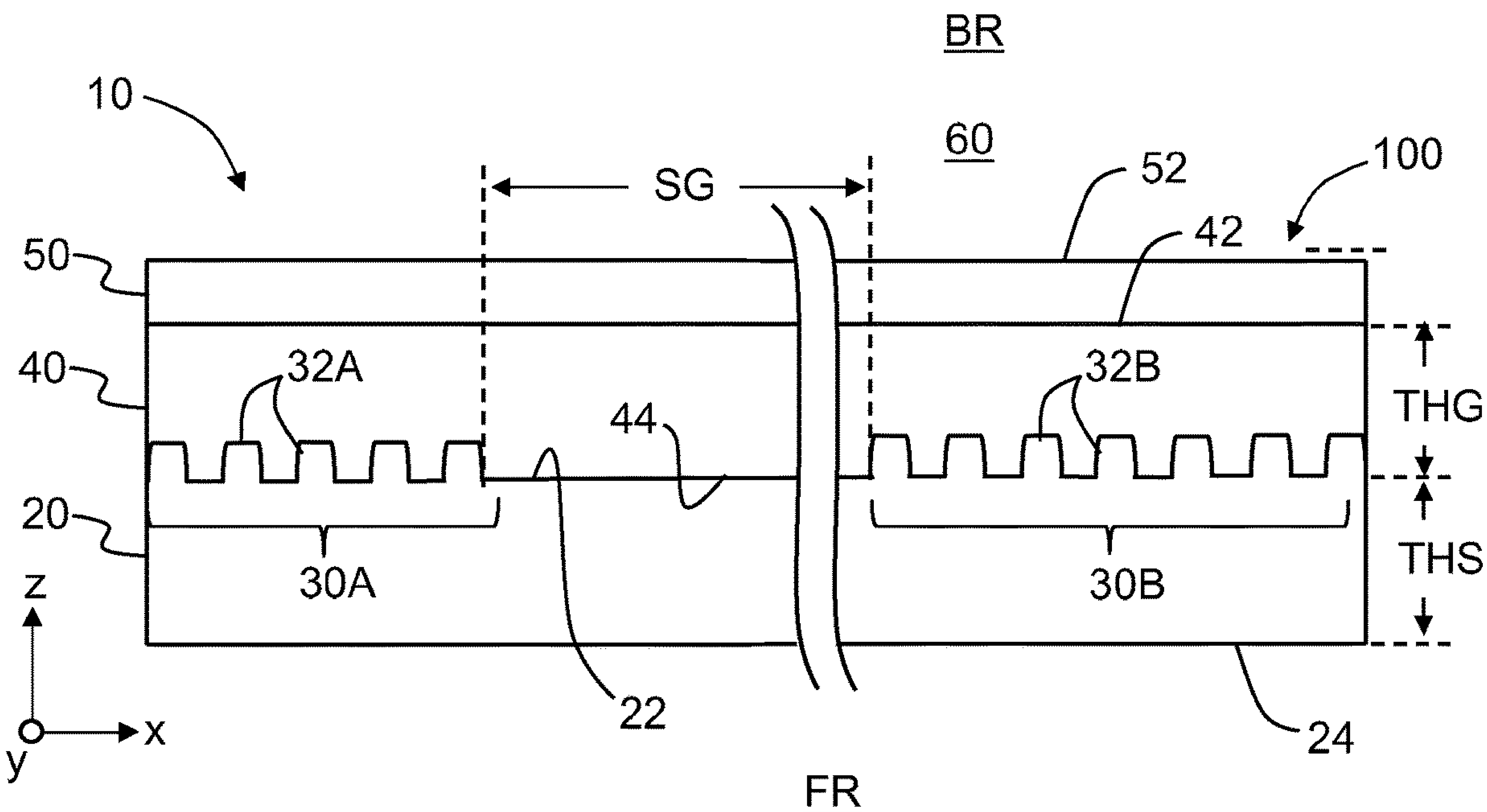
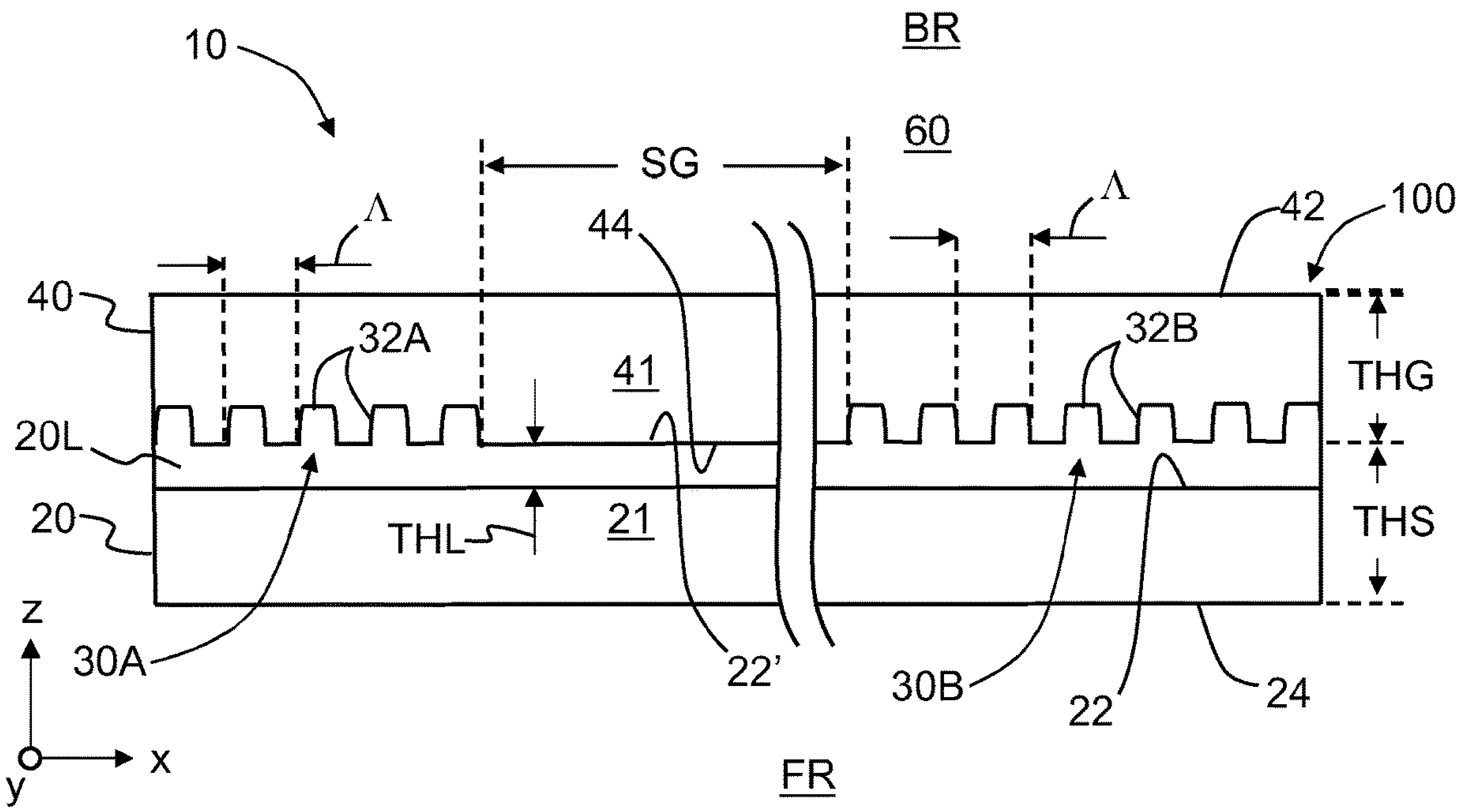
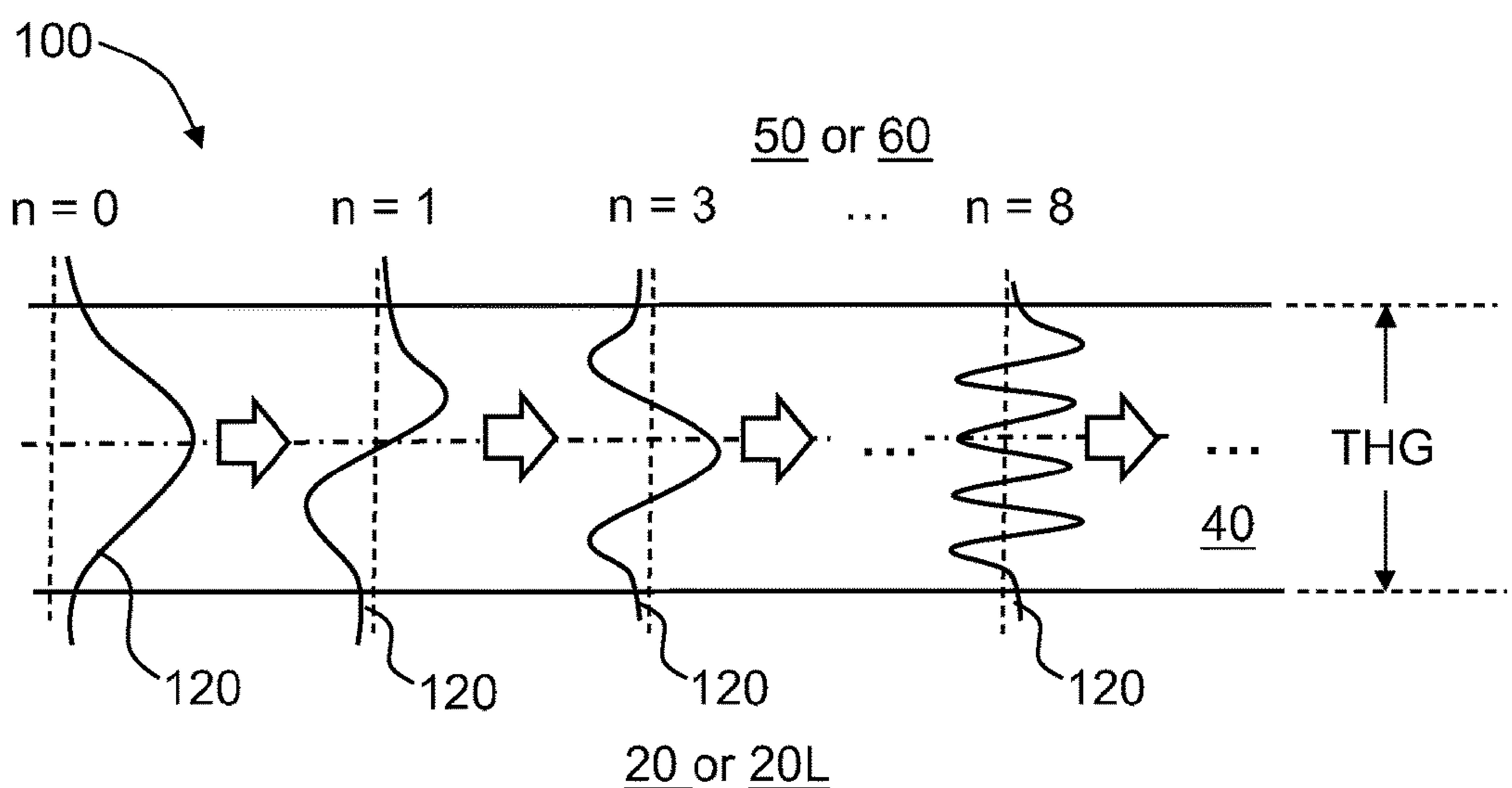

BR
60
10
SG
52
100
42
50
40
32A
32B
THG
44
20
30A
30B
THS
z
x
y
22
24
FR

FIG. 3



10
BR
60
SG
Λ
44
42
100
40
32A
41
32B
THG
20L
20
THL
21
THS
z
30A
22'
30B
22
24
y
x
FR

FIG. 4



100
50 or 60
n = 0
n = 1
n = 3
...
n = 8
THG
40
120
120
120
120
20 or 20L

FIG. 5

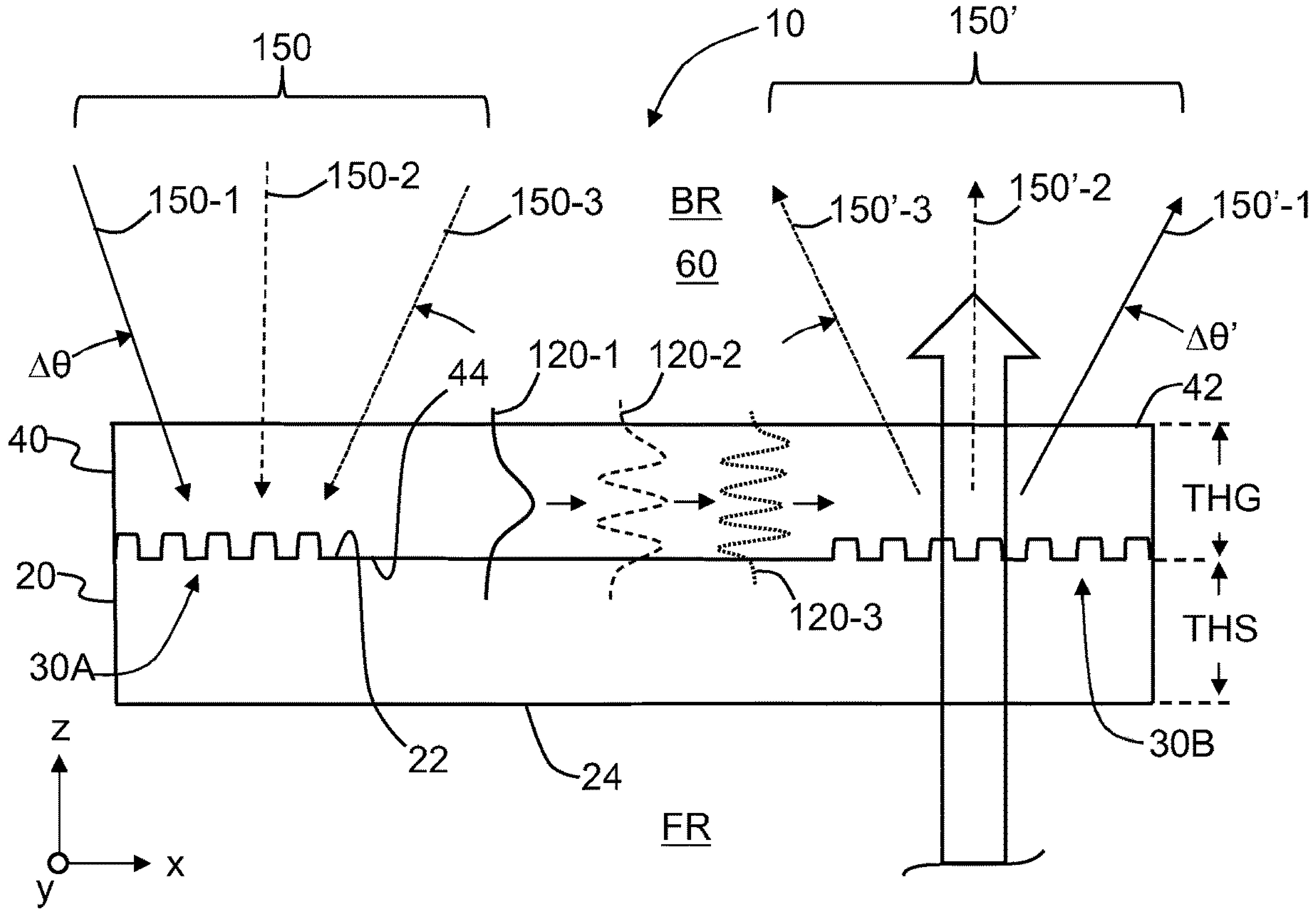


FIG. 6A

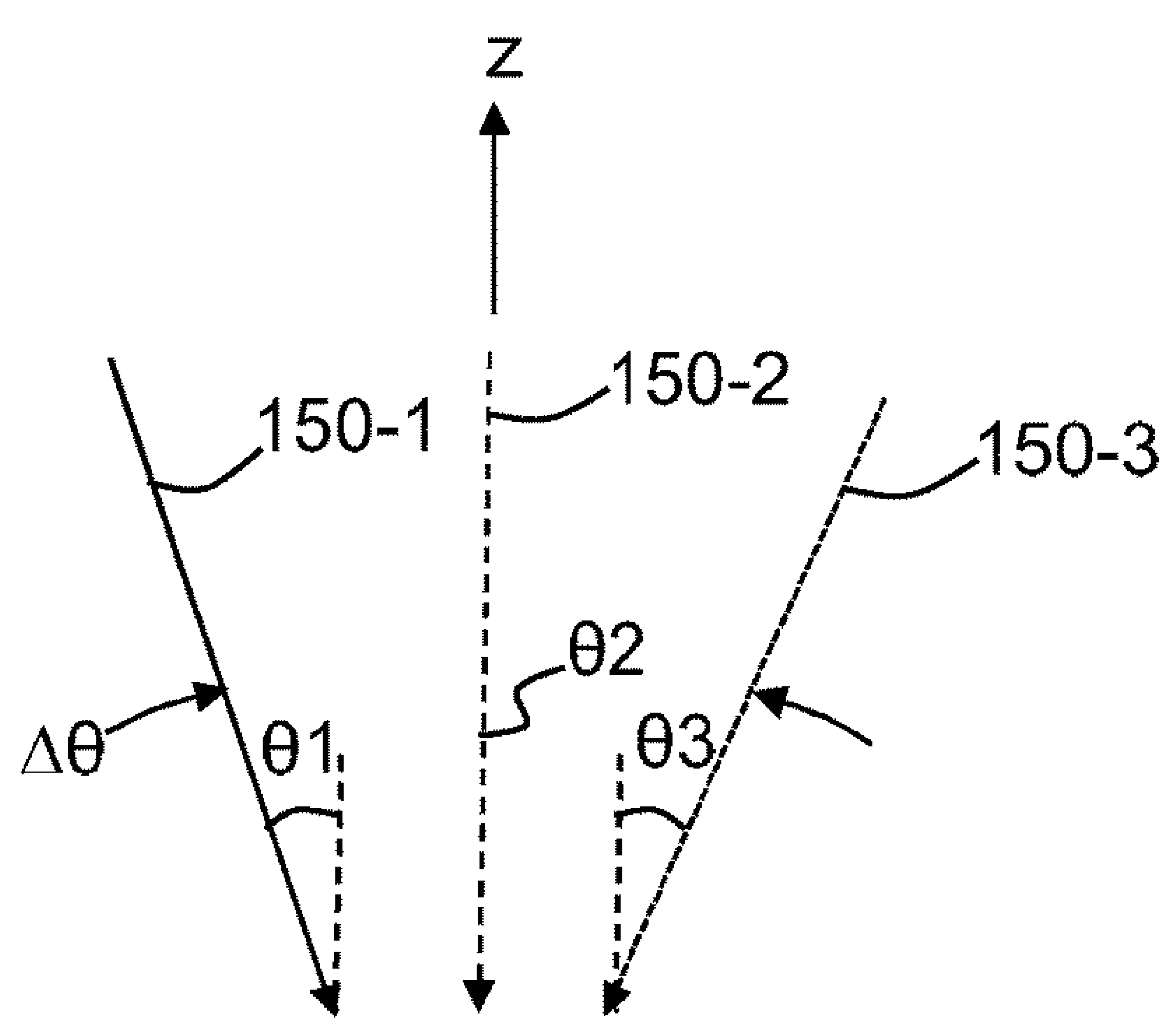


FIG. 6B

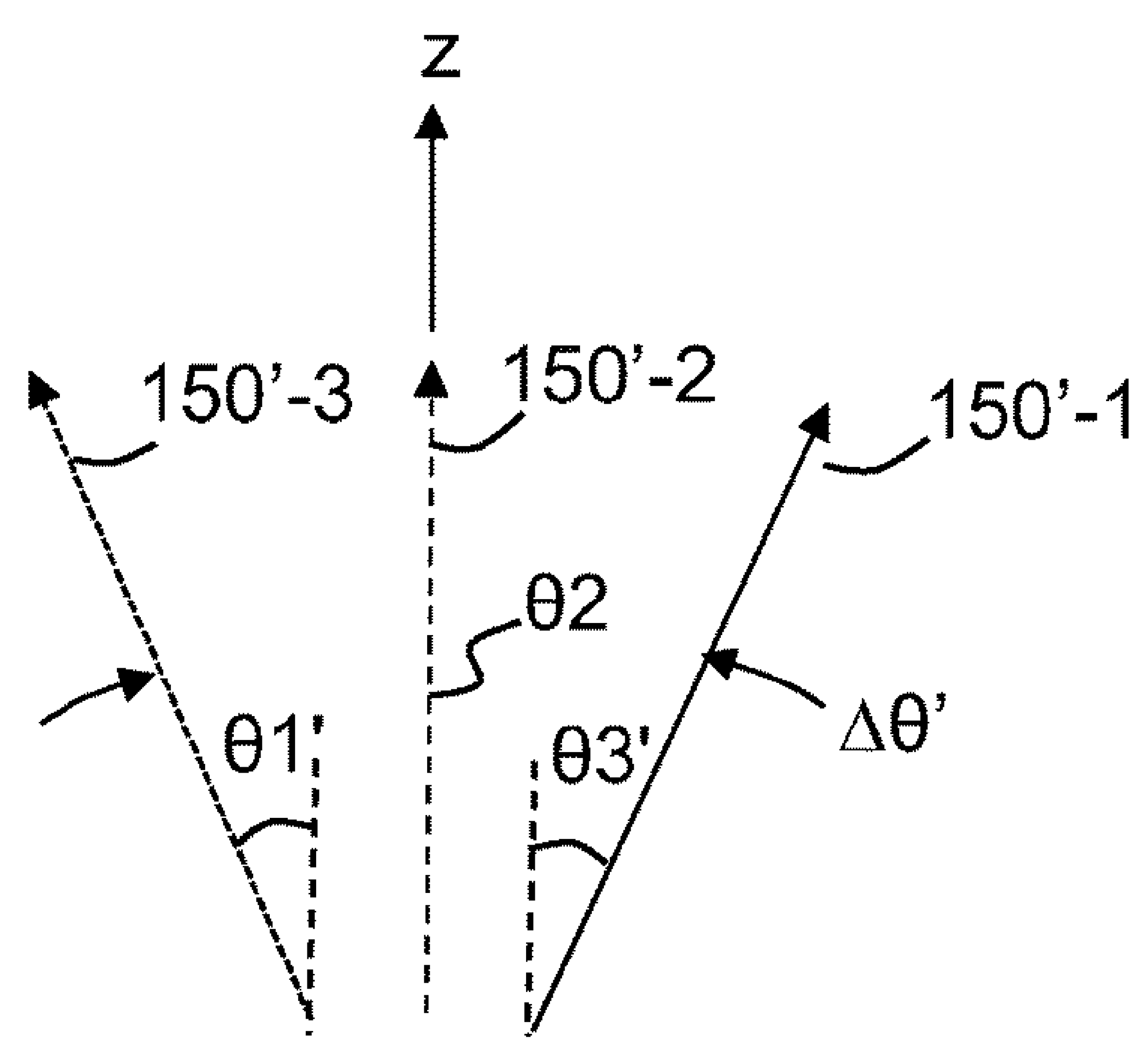


FIG. 6C

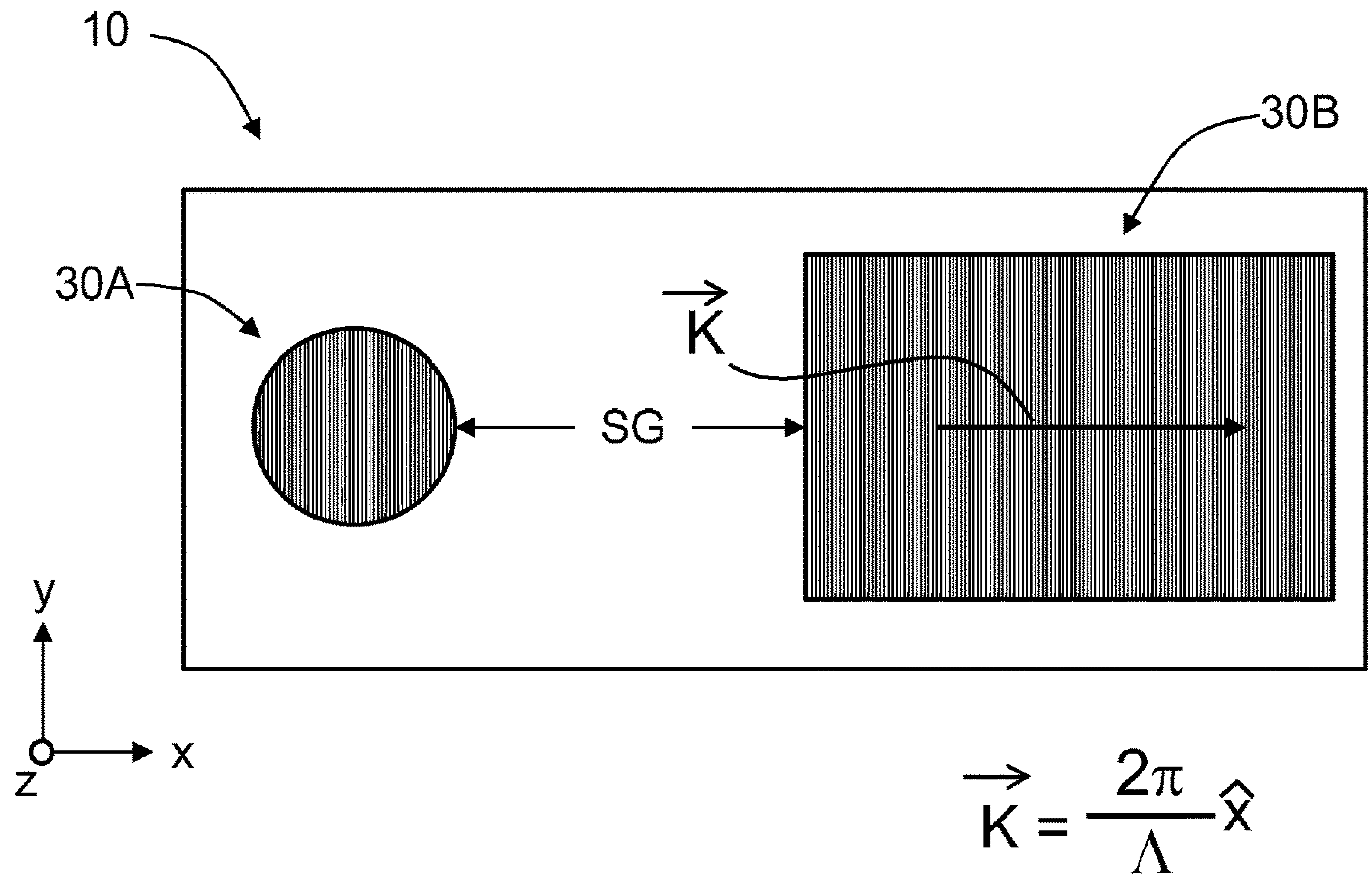

10
30B
30A
$\vec{K}$
SG
y
x
z
$\vec{K} = \frac{2\pi}{\Lambda}\hat{x}$

FIG. 7A

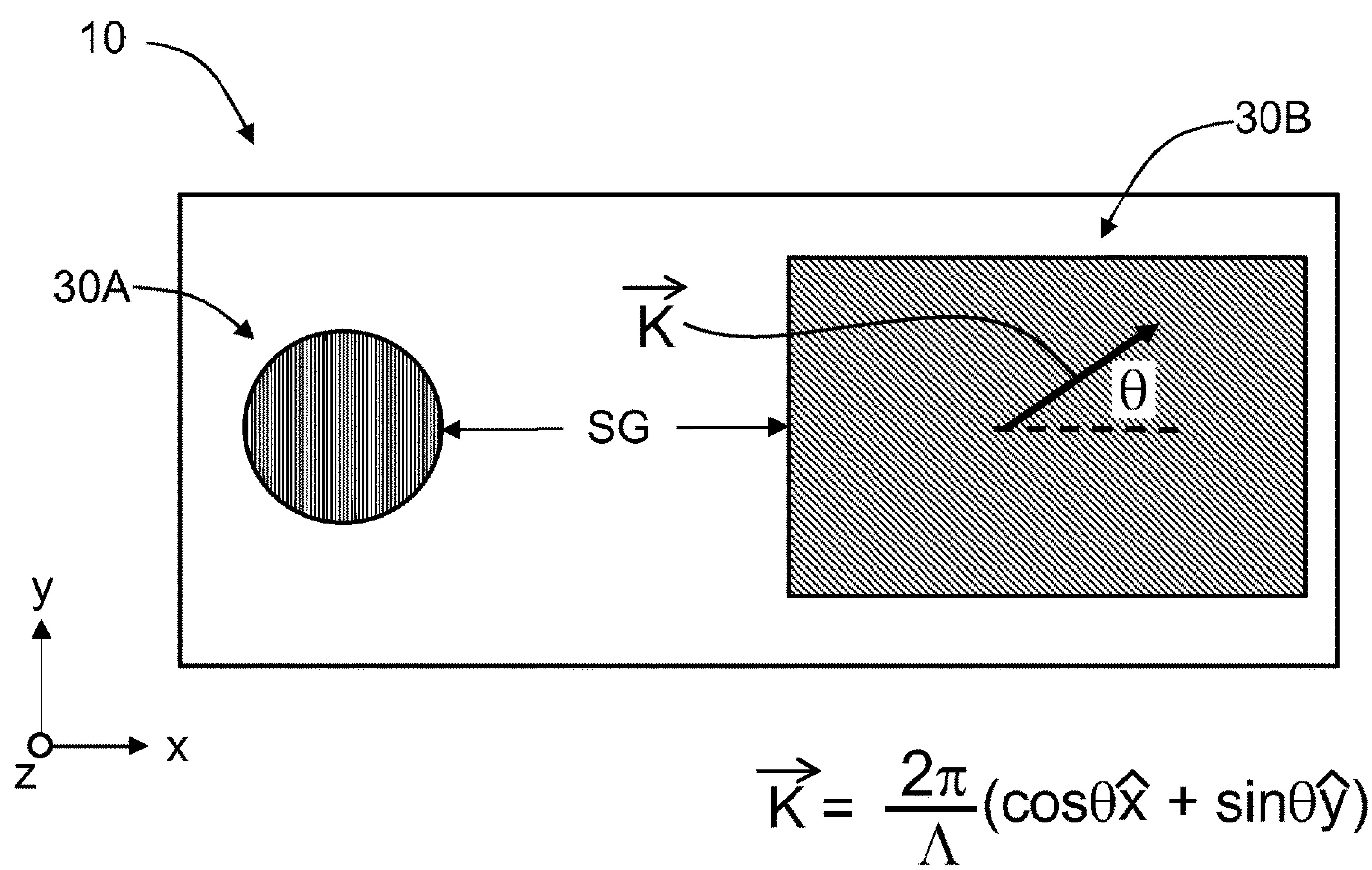
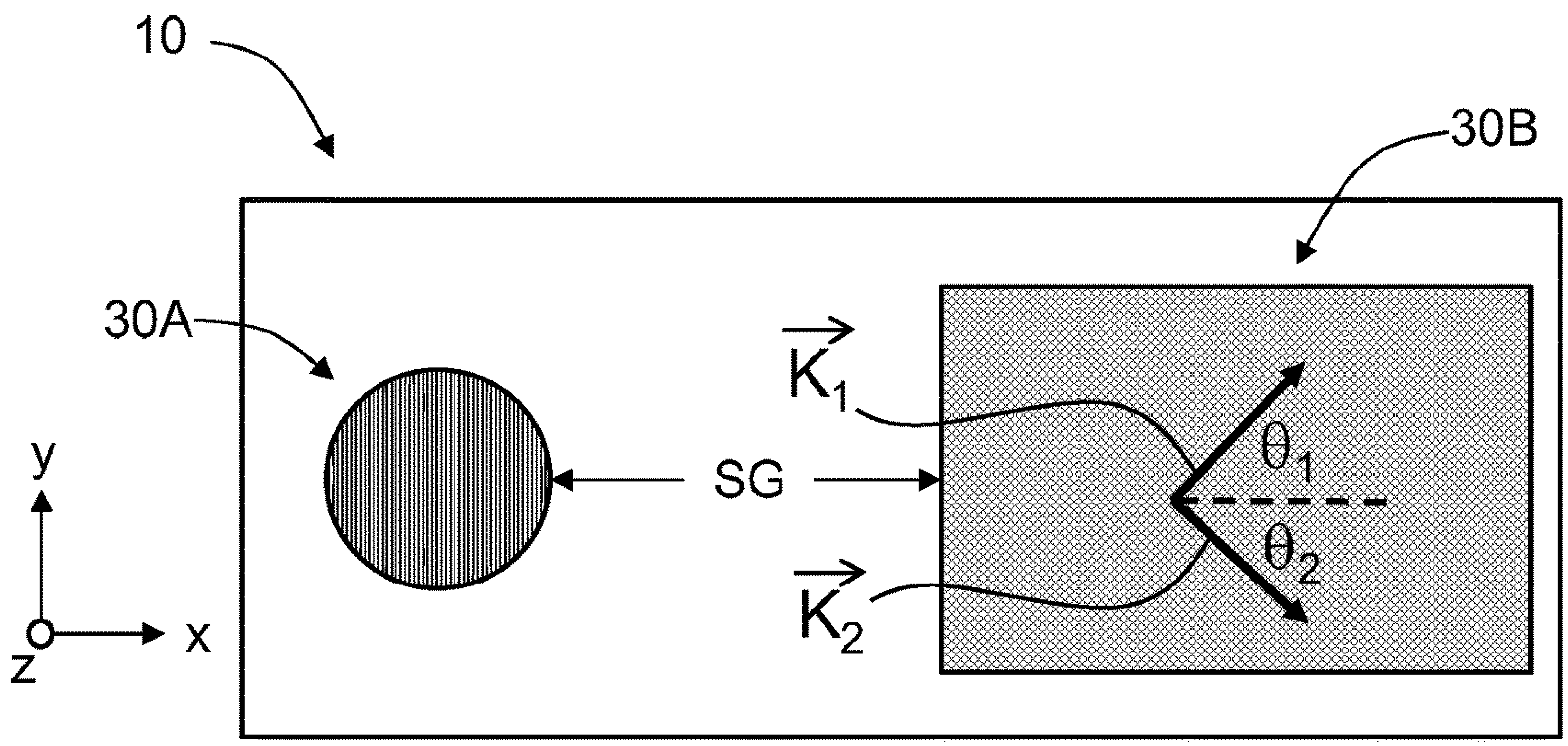

10
30B
30A
$\vec{K}$
θ
SG
y
x
z
$\vec{K} = \frac{2\pi}{\Lambda}(\cos\theta\hat{x} + \sin\theta\hat{y})$

FIG. 7B



$$\vec{K}_1 = \frac{2\pi}{\Lambda_1}(\cos\theta_1\hat{x} + \sin\theta_1\hat{y}) \qquad \vec{K}_2 = \frac{2\pi}{\Lambda_2}(\cos\theta_2\hat{x} + \sin\theta_2\hat{y})$$

FIG. 7C

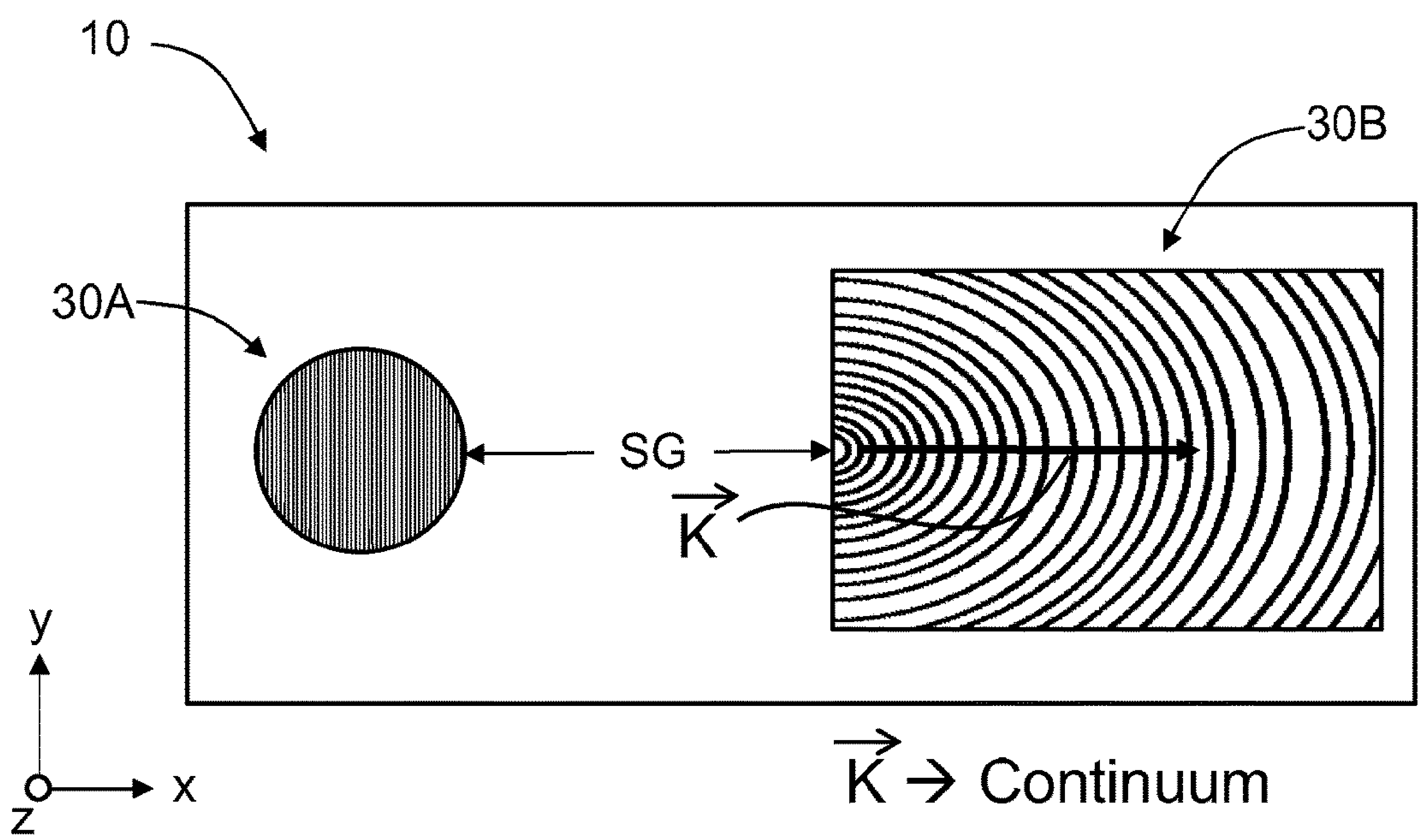


FIG. 7D

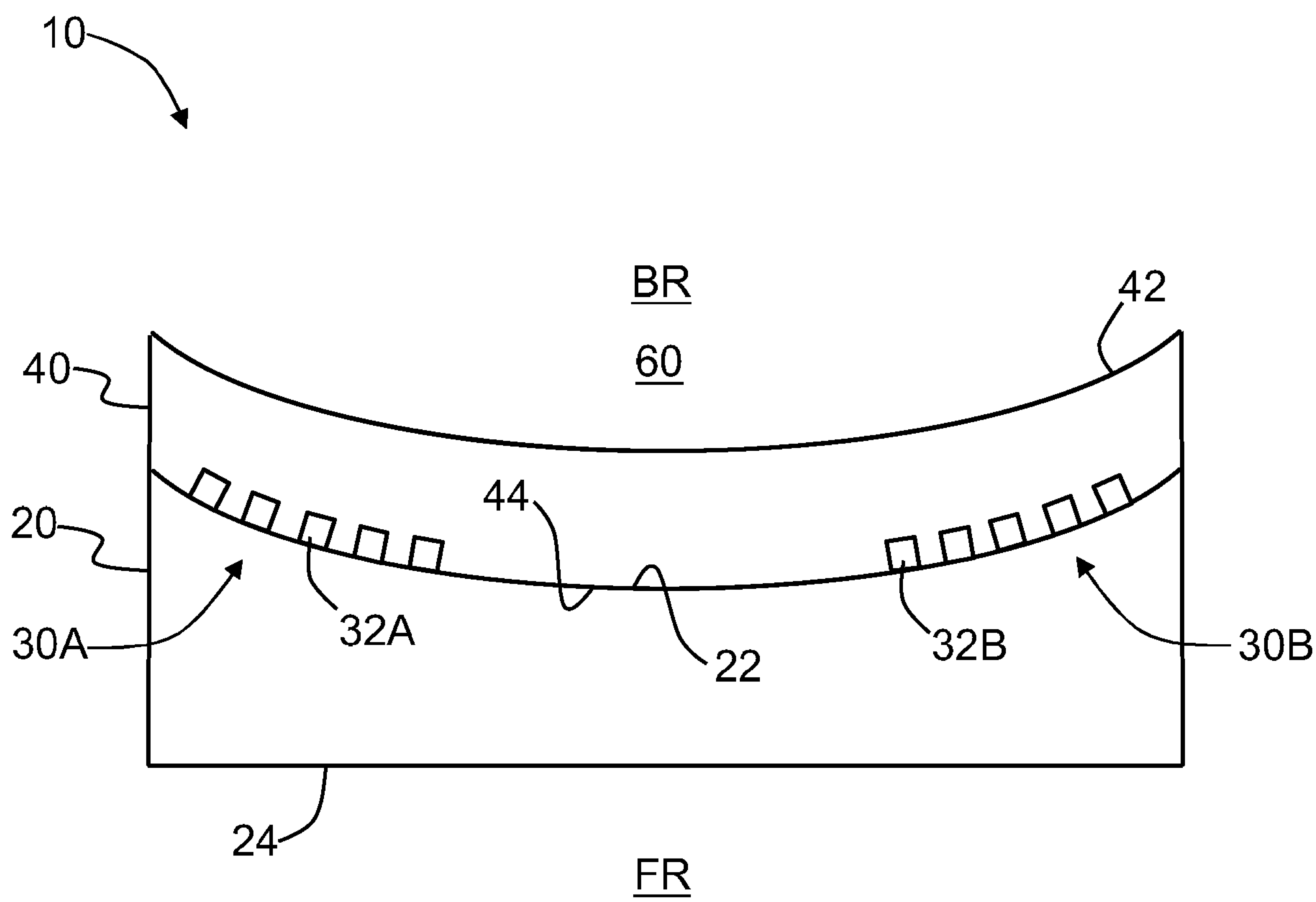
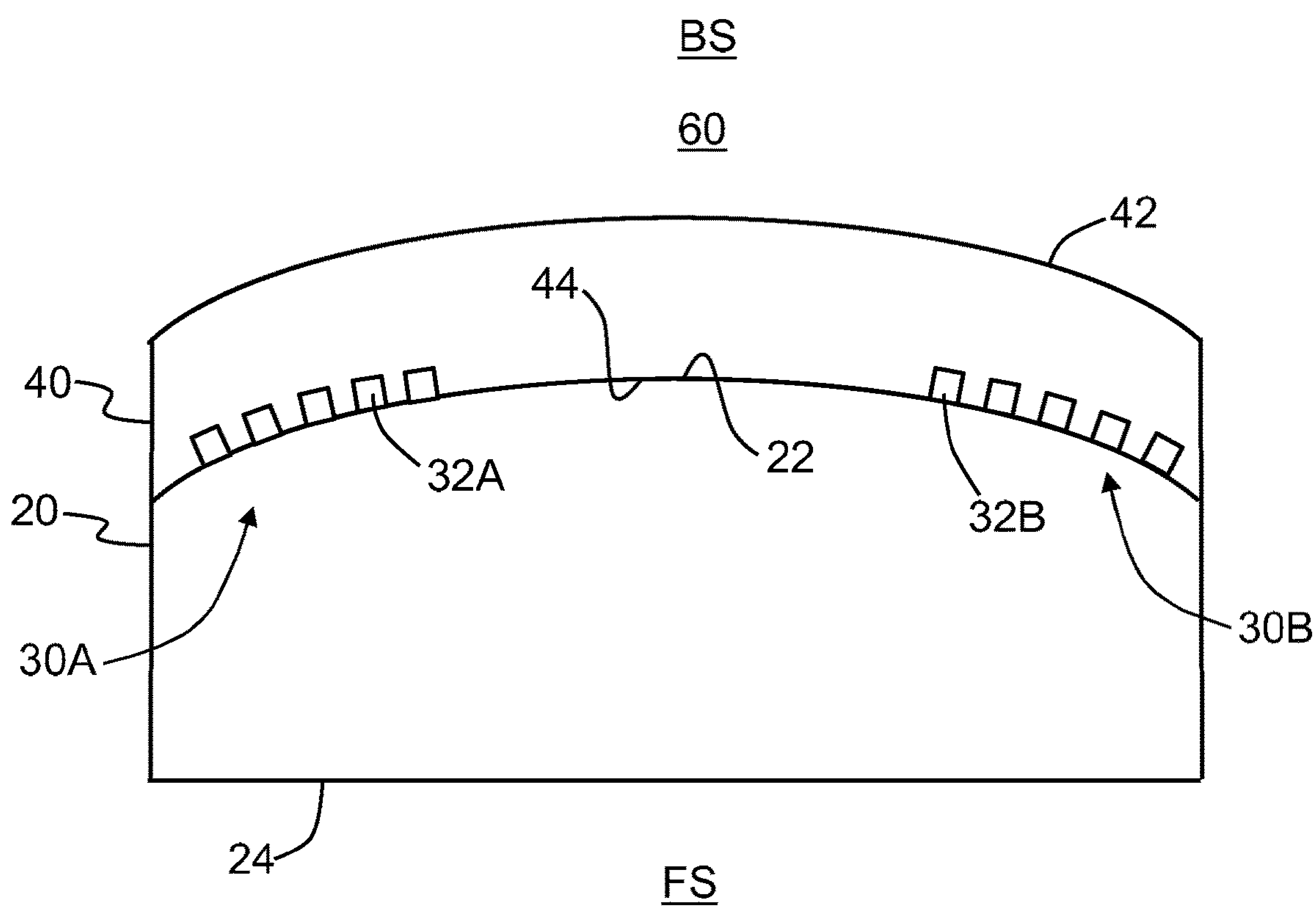
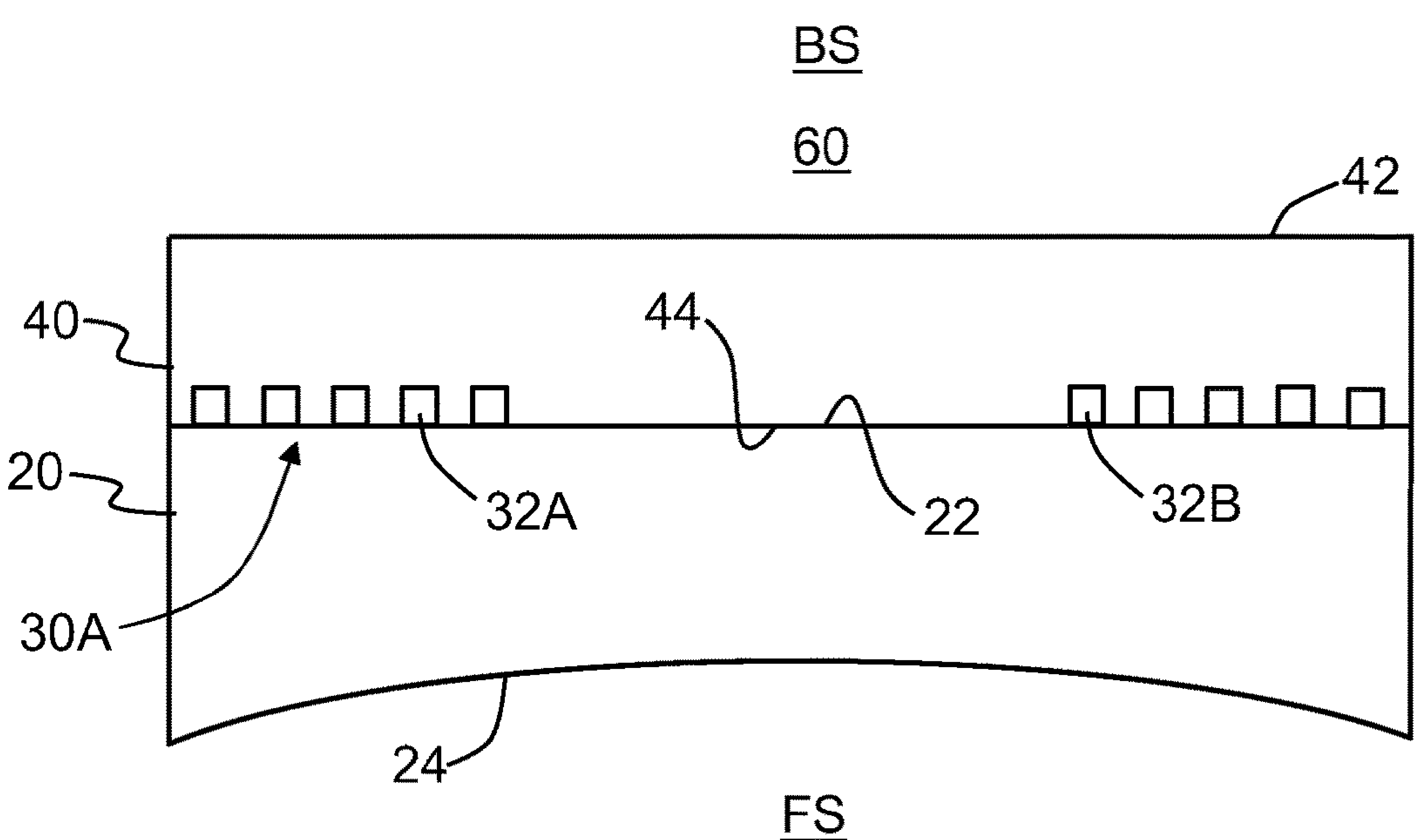


FIG. 8



BS
60
42
44
40
22
32A
32B
20
30A
30B
24
FS

FIG. 9



BS
60
42
40
44
20
32A
22
32B
30A
24
FS

FIG. 10

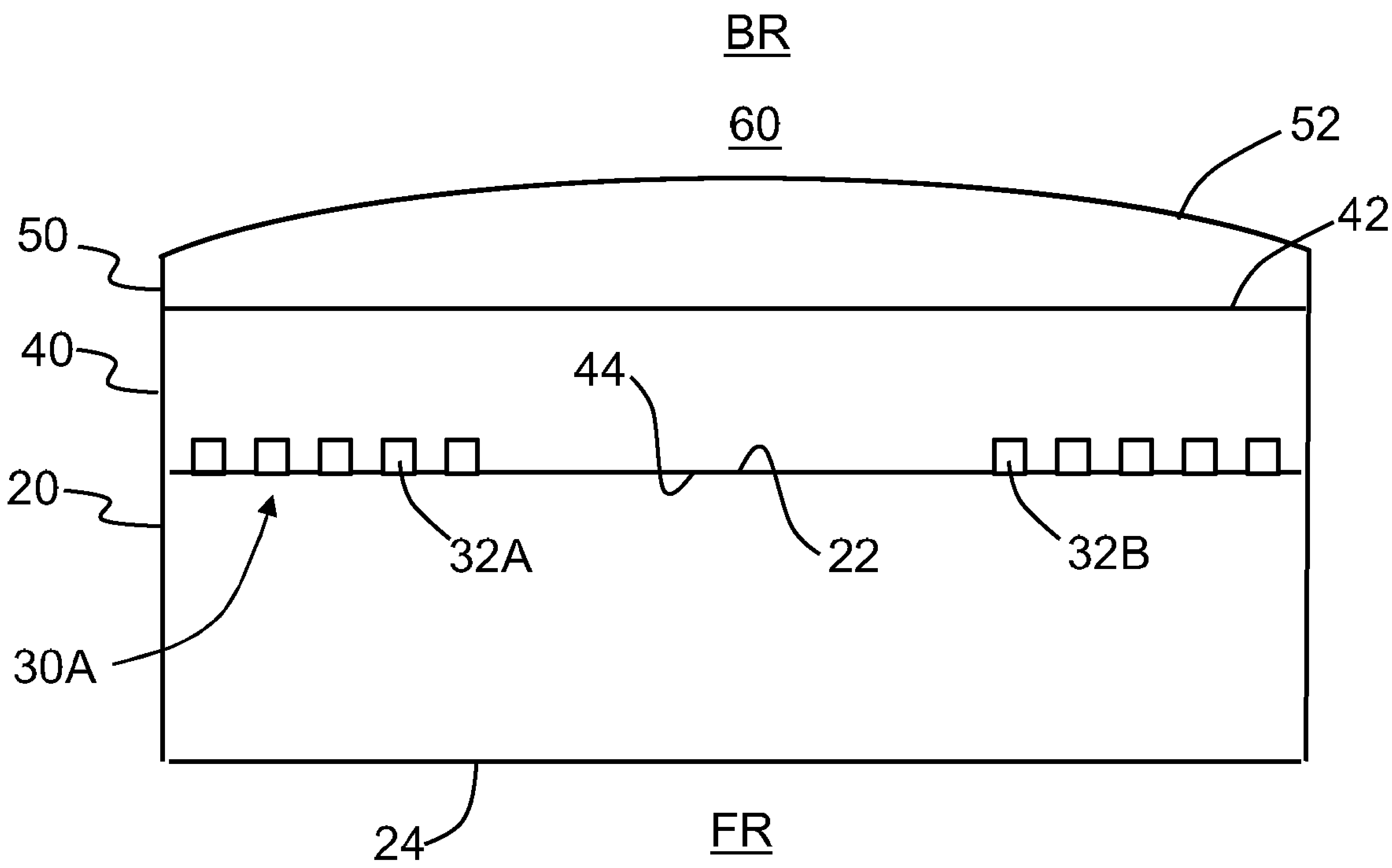

BR
60
52
50
42
40
44
20
32A
22
32B
30A
24
FR

FIG. 11

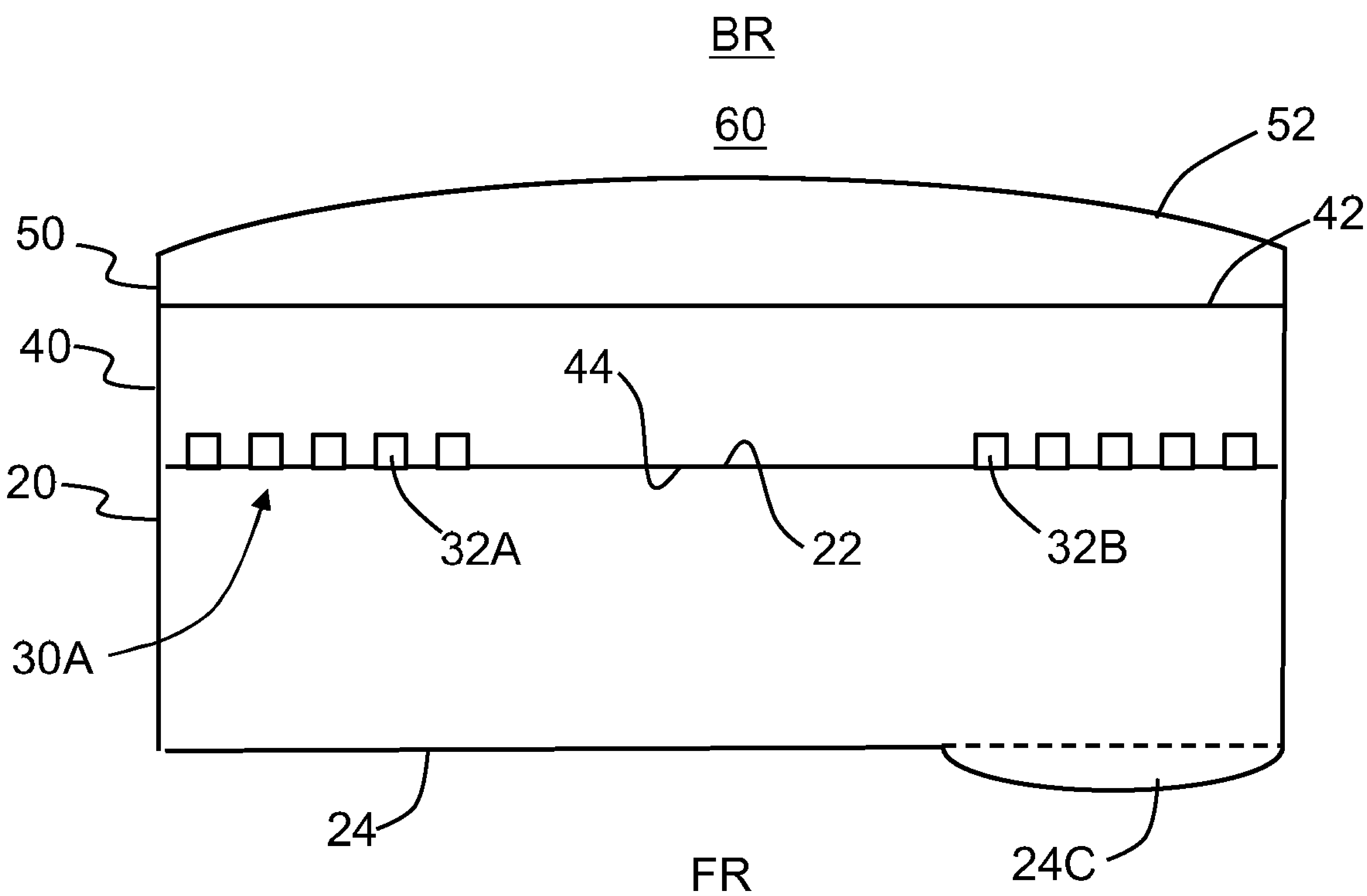

BR
60
52
50
42
40
44
20
32A
22
32B
30A
24
24C
FR

FIG. 12

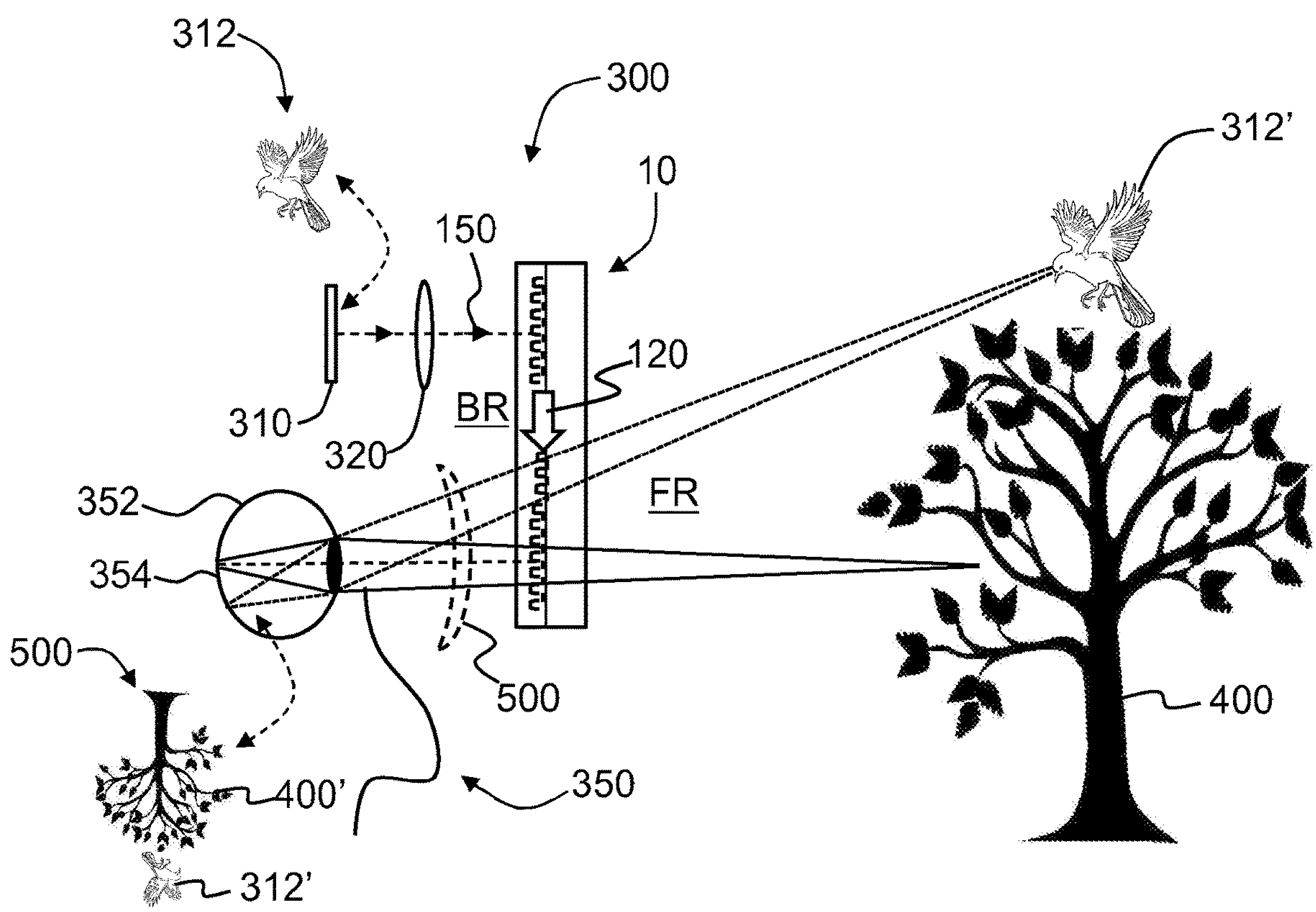


FIG. 13A

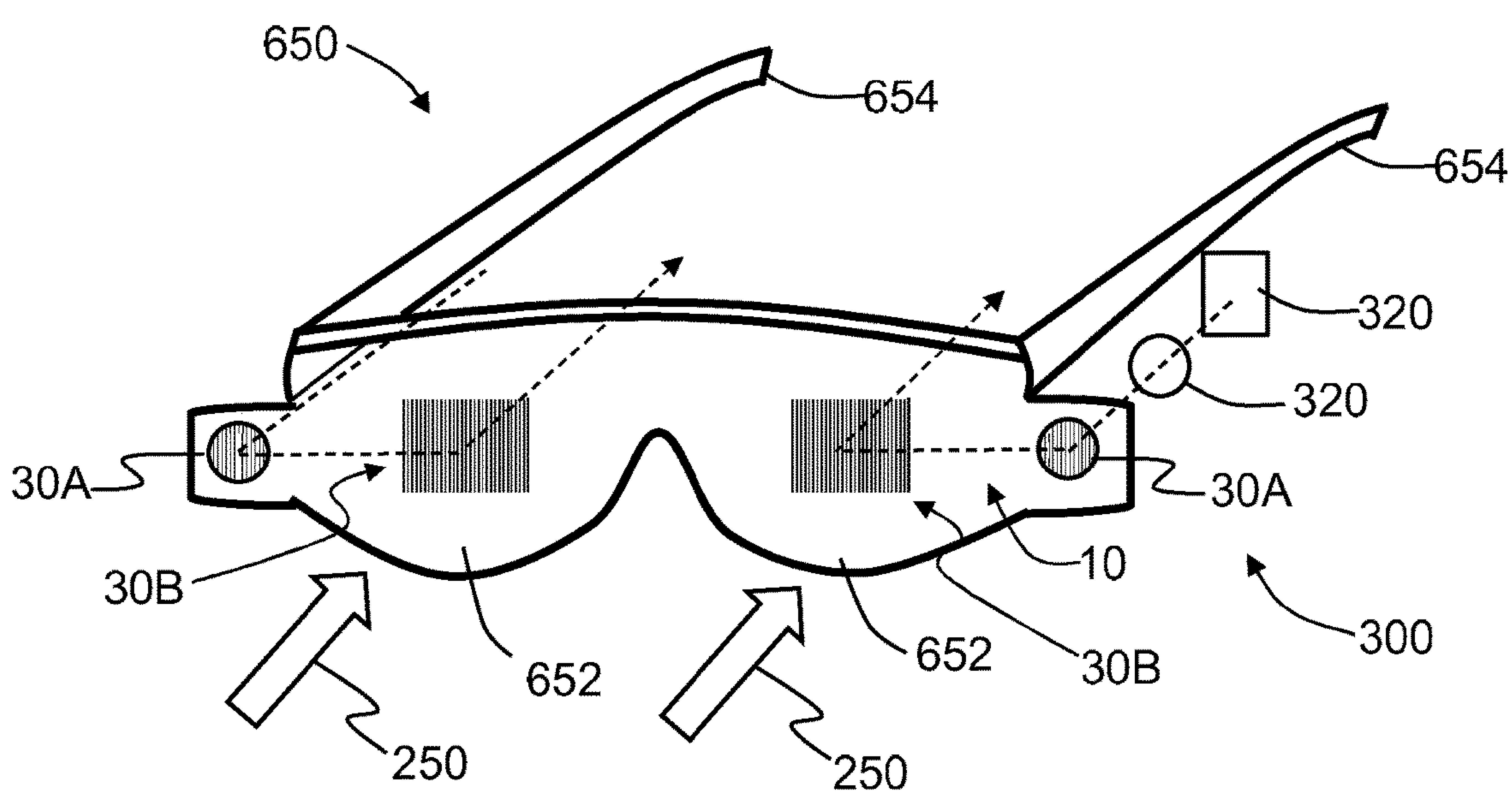


FIG. 13B

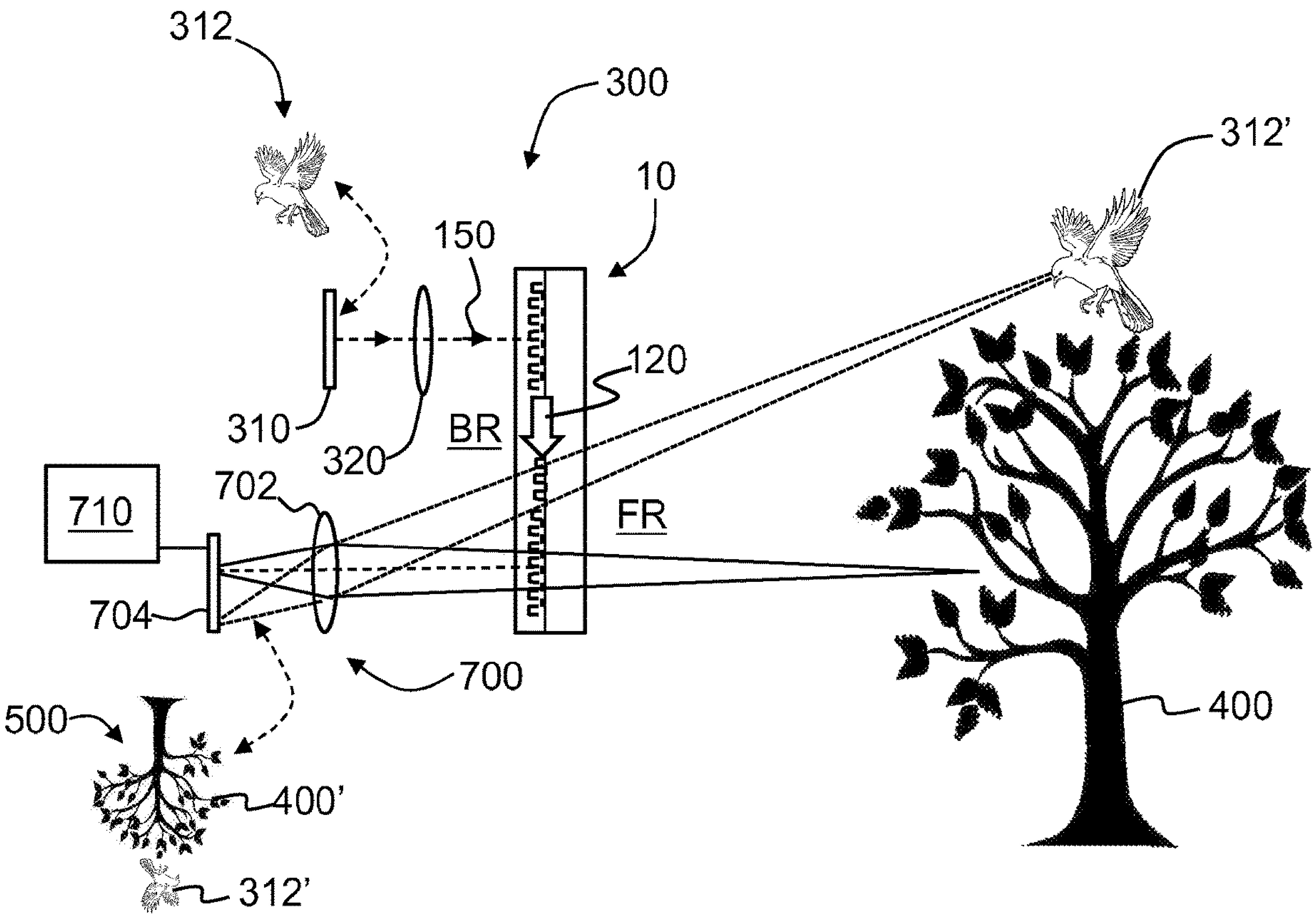

312
300
312'
10
150
120
310
320
BR
710
702
FR
704
700
500
400
400'
312'

FIG. 14

WAVEGUIDE-BASED OPTICAL SYSTEMS AND METHODS FOR AUGMENTED REALITY SYSTEMS

This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Ser. No. 62/572,109, filed on Oct. 13, 2017, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

The present disclosure relates to augmented reality (AR) systems, and in particular to waveguide-based optical systems and methods for AR systems.

BACKGROUND

AR systems are used to add virtual objects to a real visual scene being observed by a user. An example type of AR system is wearable and utilizes eyewear in the form of eyeglasses, goggles or a helmet worn by a user, and are sometimes referred to as head-mounted display (HMDs) systems. The AR system usually includes an optical system configured to allow for viewing an object or a scene while also adding an augmenting object to the actual object or to the scene being viewed directly.

AR systems typically perform five main functions. The first is to place the augmenting object away from the user's eye. The second is to transform the augmented object into a scale invariant and shift invariant form. The third is to shift the transformed augmenting object in front of the user's eye while allowing the light rays from the real scene to pass through undisturbed. The fourth is to scale the transformed and shifted augmenting object to maximize the eye box in front of the user's eye. The fifth is to combine rays from both the real scene and transformed, shifted, and scaled augmenting object and allow the user's eye to form a real image of the augmented scene.

Several different optical system designs for AR systems have been proposed, including those that employ various combinations of one or more types of optical elements such as beam splitters, off-axis lenses, mirrors (including micro-mirrors), light guides, diffractive optical elements (DOEs), and holographic optical elements (HOEs).

The use of light guides is advantageous in that they can provide for compact designs that are especially useful for AR eyewear. However, the light guides employed to date tend to be relatively thick, i.e., they are described by the principles of geometric optical rather than by the electromagnetic theory of waveguides. As such, they have a relatively limited (narrow) field of view (e.g., in the 30° to 50° range) and must be made to very tight geometrical tolerances (e.g., micron scale) so that the outputted light provides a high-quality image. In addition, the outcoupling of light from a light guide is discrete rather continuous over the output region of the light guide due to the light traversing the light guide as light rays rather than as true guided waves.

SUMMARY

Disclosed herein is an AR optical system for use in an AR system to form an augmented image of an object or a scene being viewed by a user. The AR optical system comprises a waveguide structure that includes a waveguide layer supported by a substrate. An input grating and an output grating reside within the waveguide layer and are laterally spaced apart. Input light from a display is made incident upon the input grating. The input light is coupled into the waveguide layer and travels therein as multiple guided modes to the output grating. The input and output gratings provide phase matching so that the guided modes are coupled out of the waveguide layer by the output grating continuously along the output grating to form output light. Meantime, light from a scene is transmitted perpendicularly through the output grating so that the output light and the light from the scene are combined by the eye of a user to form an augmented reality image.

An aspect of the disclosure is an augmented reality optical system for use in an augmented reality system at an operating wavelength. The system comprises: a substrate having an index of refraction n_S at the operating wavelength, a top surface and a bottom surface; an input grating and an output grating each formed either in or on the top surface of the substrate and laterally spaced apart from each other; a waveguide layer having a body, a top surface, a bottom surface and a thickness 1 μm≤THG≤100 μm, with the bottom surface of the waveguide layer supported on the top surface of the substrate so that the input and output gratings extend into the waveguide layer, and wherein the waveguide layer has an index of refraction $n_G \geq n_S$ at the operating wavelength and supports multiple guided modes; and wherein the input and output gratings provide phase matching so that input light that is incident upon the input grating is coupled into the waveguide layer and travels in the guided modes to the output grating, and is coupled out of the waveguide layer by the output grating as output light.

Another aspect of the disclosure is an augmented reality system for viewing an object or a scene and that comprises the augmented reality optical system described above and having a front region and a back region; a display apparatus disposed in the back region and that generates the input light; and a coupling optical system operably arranged relative to the display apparatus and configured to direct the input light to the input grating of the augmented reality optical system over an input field of view.

Another aspect of the disclosure is an augmented reality optical system, comprising: a waveguide structure comprising a waveguide layer of refractive index n_G and a thickness THG in the range 1 μm≤THG≤100 μm, the waveguide structure supported on a substrate having a refractive index n_S, wherein $n_G - n_S \geq 0.5$, and wherein the waveguide structure supports multiple guided modes; and an input grating and an output grating that each reside within the waveguide layer, wherein the input and output gratings provide phase matching and are laterally spaced apart from one another.

Another aspect of the disclosure is a method of forming an augment reality image when viewing an object or a scene. The method comprises: directing display light from a display image to an input grating of a waveguide structure over an input field of view to form multiple guided modes that travel in the waveguide structure; outcoupling the multiple guide modes over an output field of view using an output grating of the waveguide structure, wherein the output grating is phase matched to and spaced apart from the input grating; viewing the object or the scene with an imaging optical system through the output grating while receiving the output light from the output grating with the imaging optical system; and forming with the imaging optical system an augmented image that combines the display image and an image of the object or the scene.

The AR optical systems and AR systems disclosed herein have advantages over conventional AR optical systems and AR wearable systems. One advantage is that the waveguide

structure allows for the AR optical system to have a relatively slim form factor, which is important for AR wearable systems such as AR eyeglasses and AR goggles. Another advantage is that that waveguide structure can be deformed (bent) without substantial adverse effects on imaging. Another advantage is that the materials used are inexpensive and the designs relatively easy to fabricate. Another advantage is that the waveguide structure allows for relatively large FOVs, e.g., from 50° to 70°. Another advantage is that the relatively thin design allows for excellent transmission of the light from the object or scene being viewed through the AR optical system. Yet another advantage is that the waveguide structure allows for substantially continuous light extraction over the length of the output grating as compared to a conventional light guide where the light extraction is discrete due to the light-ray-based functionality of light guides.

Additional features and advantages are set forth in the Detailed Description that follows, and in part will be apparent to those skilled in the art from the description or recognized by practicing the embodiments as described in the written description and claims hereof, as well as the appended drawings. It is to be understood that both the foregoing general description and the following Detailed Description are merely exemplary, and are intended to provide an overview or framework to understand the nature and character of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are included to provide a further understanding, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiment(s), and together with the Detailed Description explain the principles and operation of the various embodiments. As such, the disclosure will become more fully understood from the following Detailed Description, taken in conjunction with the accompanying Figures, in which:

FIG. **1** is an elevated schematic view of an example waveguide-based AR optical system according to the disclosure.

FIG. **2** is a cross-sectional view of the example AR optical system FIG. **1**.

FIG. **3** is a cross-sectional view of an example AR optical system similar to that of FIG. **2** and that further includes a cap layer.

FIG. **4** is a cross-sectional view of an example AR optical system similar to that of FIG. **2** and further includes a low-index layer that resides immediately adjacent the bottom surface of the waveguide layer.

FIG. **5** is a schematic diagram of a portion of an example waveguide structure of the AR optical system illustrating multiple guided modes traveling mainly within the waveguide layer.

FIG. **6**A is similar to FIG. **2** and illustrates the basic principles of operation of the AR optical system disclosed herein.

FIG. **6**B is a close-up view of the input light showing the input angular range and three example input angles within the input angular range.

FIG. **6**C is a close-up view of the output light showing the output angular range and three example output angles within the output angular range.

FIGS. **7**A through **7**D are top-down views of example configurations for the input grating and the output grating of the AR optical system disclosed herein.

FIGS. **8** through **12** are schematic cross-sectional diagrams of example AR optical systems that include at least one curved surface.

FIG. **13**A is a schematic diagram of an example embodiment of an AR system that includes the AR optical system disclosed herein as used by a user, wherein the eye of the user constitutes the imaging optical system.

FIG. **13**B is a schematic diagram of example AR eyewear that incorporates the AR system disclosed herein and that can be worn by the user.

FIG. **14** is similar to FIG. **13**A and illustrates an example where the AR system includes an imaging optical system that includes an imaging lens and an image sensor rather than the eye of the user as shown in FIG. **13**A.

DETAILED DESCRIPTION

Reference is now made in detail to various embodiments of the disclosure, examples of which are illustrated in the accompanying drawings. Whenever possible, the same or like reference numbers and symbols are used throughout the drawings to refer to the same or like parts. The drawings are not necessarily to scale, and one skilled in the art will recognize where the drawings have been simplified to illustrate the key aspects of the disclosure.

The claims as set forth below are incorporated into and constitute part of this Detailed Description.

Cartesian coordinates are shown in some of the Figures for the sake of reference and are not intended to be limiting as to direction or orientation.

In the description below, λ denotes an operating wavelength of light, while $\Delta\lambda$ denotes an operating wavelength range of light (i.e., a spectral band) that includes the operating wavelength. Also, θ denotes an angle while $\Delta\theta$ denotes an angular range, which in an example denotes the field of view (FOV).

The various refractive indices cited below are for the operating wavelength λ, which in an example is a visible wavelength. In an example, the spectral band $\Delta\lambda$ comprises visible wavelengths.

AR Optical System

FIG. **1** is an elevated schematic view of an example waveguide-based AR optical system ("AR optical system") **10** according to the disclosure, while FIG. **2** is a cross-sectional view of the example AR optical system of FIG. **1**. The AR optical system has a length LZ in the x-direction, a length LY in the y-direction and an overall thickness TH in the z-direction, as best seen in FIG. **1**.

The AR optical system **10** has a substrate **20** with a body **21**, a top surface **22** and a bottom surface **24**. The body **21** of substrate **20** has an index of refraction n_S and a thickness THS. In the example shown, the substrate **20** is planar, though other non-planar configurations can be used as described below.

The top surface **22** of the substrate includes a first grating **30**A made up of first grating elements **32**A and a second grating **30**B made up of grating elements **32**B. The first and second gratings are spaced apart in the x-direction by a spacing (distance) SG. The first grating **30**A is referred to herein as the "input" or "entrance pupil" grating while the second grating **30**B is referred to herein as the "output or "exit pupil" grating. The input and output gratings **30**A and **30**B each have the same period Λ and grating height h.

In one example, one or both of the first and second grating elements **32**A and **32**B are formed in the substrate so that the first and second grating elements are made of the substrate material. This can be accomplished using a masking process, an etching process, a replication process, or a molding process. In another example, one or both of the first and second grating elements **32**A and **32**B are added to the top surface of the substrate, e.g., via selective deposition process or a replication process. Deposited or replicated first and/or second grating elements **32**A and **32**B can be made of a variety of materials, e.g. inorganic materials such as oxides or organic materials such as acrylates, with substantially the same refractive index as the substrate **20**. As discussed below, the input and output gratings **30**A and **30**B provide phase matching with respect to light inputted and outputted from the AR optical system **10**, as described in greater detail below.

The AR optical system **10** also includes a waveguide layer **40** that resides immediately upon the top surface **22** of the substrate **20**. The waveguide layer **40** has a body **41**, top surface **42** and a bottom surface **44**, which interfaces (i.e., is in contact with) the top surface **22** of the substrate **20**. Thus, a first portion of the body **41** fills the spaces between the first grating elements **32**A while a second portion of the body fills the spaces between the second grating elements **32**B. The waveguide layer **40** has a refractive index n_G, wherein $n_G > n_S$. The waveguide layer **40** has a thickness THG.

In an example configuration of the AR optical system **10**, the top surface **42** of the waveguide layer **40** interfaces with an ambient environment **60**, which in one example comprises air having a refractive index $n_A \approx 1$. In another example configuration illustrated in FIG. **3**, the top surface **42** of the waveguide layer **40** is interfaced with a cap layer **50** having a refractive index $n_C < n_G$. The cap layer **50** has a top surface **52** and a bottom surface **54**, which is in contact with the top surface **42** of the waveguide layer.

The substrate **20**, waveguide layer **40** and either the optional cap layer **50** or the ambient environment **60** define a waveguide structure **100** wherein light can propagate within the waveguide layer as guided waves that travel in different guided modes, as described in greater detail below.

The AR optical system **10** has a front region FR immediately adjacent the bottom surface **24** of the substrate **20**. The AR optical system **10** also has a back region BR immediately adjacent either the top surface **42** of the waveguide layer **40** or the top surface **52** of the cap layer **50**, depending on whether the cap layer **50** is used in the AR optical system.

In an example, the substrate index of refraction (i.e., the refractive index of the body **21** of the substrate) $n_S \leq 1.5$. In an example, the substrate **20** can be made from a conventional glass, such as fused silica. In other examples, the substrate **20** can be made from a plastic or a polymer. In an example, the substrate **20** can be made of a thermoplastic.

Also In an example, the waveguide layer refractive index $n_G \geq 2$. In an example, $n_G - n_S \geq 0.5$. The waveguide layer **40** can also be made of at least one oxide or a combination of a least one oxide material and at least one fluoride material. Example oxide materials for the waveguide layer **40** include thin-films, such as Ta_2O_5 and TiO_2.

FIG. **4** is similar to FIG. **3** and illustrates an example configuration wherein waveguide structure **100** includes a low-index layer **20**L having a refractive index $n_L < n_S$ and a thickness THL. The low-index layer **20**L resides immediately adjacent the bottom surface **44** of the waveguide layer **40**. The low-index layer **20**L can be added to the substrate **20** on the top surface **22** or can be formed in the top surface and can be considered to define a new substrate top surface **22'** that includes or supports the input and output gratings **30**A and **30**B. In an example, the low-index layer **20**L is formed as a low-index thin film such as MgF_2, which has a refractive index $n_L = 1.38$.

The Waveguide Structure

As noted above, the waveguide structure **100** is defined by the relatively high-refractive-index waveguide layer **40** surrounded by the relatively low-refractive index of either the ambient environment **60** or the cap layer **50** at the top surface **42** and the substrate **20** or the low-index layer **20**L at the bottom surface **44**. The waveguiding properties of the waveguide structure **100** are defined mainly by the refractive indices n_G, n_S (or n_L) and n_A (or n_C), as well as by the thickness THG of the waveguide layer **40** and the operating wavelength λ of light used.

In a non-limiting example, the thickness THG of the waveguide layer **40** is in the range 1 μm≤THG≤100 m or in the range from 20 μm≤THG≤50 μm. The precise thickness THG of the waveguide layer **40** depends on the substrate refractive index n_S (or the refractive index of n_L of the low-index layer **20**L if used) and the refractive index n_C of the cap layer **50** or whether the ambient environment with refractive index n_A is used.

FIG. **5** is a schematic diagram of a portion of the waveguide structure **100**. The waveguide structure **100** differs from what is often referred to in the art as a light guide or light pipe in that the waveguide structure supports guided modes, which are properly described by the electromagnetic theory of wave propagation rather than rules of geometrical optics. As noted above, in an example the overall waveguide thickness THG of the waveguide layer **40** can be in the range from 1≤THG≤100 μm, which is relatively thin as compared to conventional light guides which, for example, have a thickness of 250 μm to 1000 μm. In an example, the waveguide thickness THG, is at least 2.5 times thinner than a conventional light guide used in conventional light-guide-based AR optical systems.

FIG. **5** includes guided waves or guided modes **120** propagating mainly in the waveguide layer **40**, with tail (evanescent) portions of the guided modes traveling in the adjacent layers. In an example, the waveguide structure **100** supports n=0, 1, 2, . . . m guided modes **120**, wherein n is the mode number and m is the highest mode number. The total number of modes is N=m+1 for a given polarization, i.e., TE or TM. The n=0 mode is the fundamental mode and the n>0 modes are the higher-order modes. FIG. **5** shows an example where m=8, which represents a total of N=9 guided modes **120** supported by the waveguide structure **100** for a given polarization.

In an example of the waveguide structure **100**, the total number N of guided modes **120** can be in the range 500≤N≤1000. The total number of modes N is selected to be large enough to provide sufficient angular resolution and sufficiently large field of view (FOV) and a substantially continuous light extraction for the output light **150'** outputted by the output grating **30**B while keeping the thickness THG of the waveguide layer **40** to be relatively small, e.g., to 100 μm or smaller. For example, the FOV can be as high as 70°, with even larger FOVs requiring a greater number N of guided modes. Likewise, smaller FOVs require fewer guided modes **120**. The AR optical system **10** can of course operate with just a few modes or tens of modes in select cases (e.g., where a relatively narrow field of view is acceptable), but it is anticipated that the AR optical system will be most useful having hundreds of modes to have a relatively large FOV.

Example AR Optical System Parameters

An example AR optical system **10** has a glass substrate **20** (e.g., a borosilicate crown such as BK7) with a substrate refractive index n_S=1.5, a waveguide layer **40** made of Ta_2O_5 and having a thickness THG=100 μm and a refractive index n_G=2.15, and an ambient air environment **60** in contact with the top surface **42** of the waveguide layer. This configuration supports about N=600 guided modes **120** at a visible operating wavelength of λ=520 nm.

In another example similar to that above but where the waveguide layer **40** is made of Nb_2O_5 and having a waveguide refractive index n_G=2.38, the waveguide structure **100** supports about N=700 modes.

In another example similar to that above but where the waveguide layer **40** is made of TiO_2 and having a refractive index n_G=2.68, the waveguide structure **100** supports about N=850 modes.

In another example similar to that above but where the substrate **20** supports a low-index layer **20**L made of MgF_2 and having a refractive index n_L=1.38 and wherein the waveguide layer **40** is made of TiO_2 having a refractive index n_G=2.68, the waveguide structure **100** supports about N=890 modes.

In the examples, the number of modes is calculated using the following equation:

$$N=(2\cdot\mathrm{THG}/\lambda)\cdot(n_G^2-n_S^2)^{1/2}.$$

Also in an example, the input and output gratings **30**A and **30**B can each have the following parameters: the grating period (or pitch) Λ in the range from 200 nm to 600 nm and the grating element height h in the range from 50 nm to 500 nm.

The Input and Output Gratings

FIG. **6**A is similar to FIG. **2** and illustrates the basic principles of operation of the AR optical system **10**. In FIG. **6**A, input light **150** is incident upon the input grating **30**A from the back region BR of the AR optical system **10**. As discussed below, the input light **150** can be generated by a display that forms a display image. Three different rays of light **150** are denoted **150-1**, **150-2** and **150-3** and correspond to different incident angles θ, which in an example can be measured relative to the z axis. Here, the light rays **150-1**, **150-2** and **150-3** can be thought of as the direction of propagation of light waves. FIG. **6**B is a close-up view of the input light **150** and shows the three different example angles θ**1**, θ**2** and θ**3** within an angular range Δθ. The input light **150-1**, **150-2** and **150-3** travels generally in the −z direction from the back region BR toward the input grating **30**A.

The input light **150-1**, **150-2** and **150-3** of different angles is incident upon and interacts with the input grating **30**A, which converts the input light into corresponding different waveguide modes **120-1**, **120-2** and **120-3** by virtue of phase matching between the waveguide modes, the input grating, and the input light at different incident angles θ**1**, θ**2** and θ**3**. Because the waveguide structure **100** supports a limited number of guided modes **120**, only input light **150** at select incident angles θ within the input angular range will couple into and travel in the waveguide layer **40** as a guided mode **120**. These angles θ are referred to as coupling angles. The greater number of guide modes **120** supported by the waveguide structure **100**, the greater number of coupling angles θ. In FIG. **6**A, only three incident (coupling) angles θ**1**, θ**2** and θ**3** are shown for ease of illustration. As noted above, one can have N=1000 different guided modes **120** so that an incident FOV defined by the input angular range Δθ can have 1000 coupling angles θ.

The waveguide modes **120-1**, **120-2** and **120-3** travel within the waveguide structure **100** to the output grating **30**B. The input and output gratings **30**A and **30**B phase match the waveguide modes **120** to the input light and output light **150** and **150'**, respectively. Thus, the waveguide modes **120-1**, **120-2** and **120-3** are coupled out of the waveguide layer **40** by the output grating **30**B as corresponding output light **150'-1**, **150'-2** and **150'-3** emitted at output angles θ**1**, θ**2** and θ**3** within an output angular range Δθ'=Δθ for output light **150'**. FIG. **6**C is a close-up view of the output light **150'** and shows the three different example output angles θ**1'**, θ**2'** and θ**3'** within an angular range Δθ'. As noted above, for N=1000, there can be 1000 different output angles θ'.

In an example when input and output gratings **30**A and **30**B have the same period Λ, then θ**1**=θ**1'**, θ**2**=θ**2'**, θ**3**=θ**3'** and Δθ=Δθ' (i.e., the coupling angles equal the corresponding output angles and the input FOV equals the output FOV). The output light **150'** travels generally in the +z direction back into the back region BR of the AR optical system **10**. Note that the output light **150'** is generally displaced in the lateral direction (in FIG. **6**A, the x-direction) by the distance SG from the input light **150**.

In an example, the input light **150** is polychromatic, i.e., has a wavelength band Δλ. An example wavelength band Δλ comprises or consists of at least a portion of the visible electromagnetic spectrum.

In the case where the input light **150** is polychromatic, each wavelength λ within the wavelength band Δλ will be coupled into the waveguide structure **100** as corresponding guided modes **120** over the input angular range Δθ. The guided modes **120** of the different wavelengths independently propagate within the waveguide structure in the same way that different wavelengths of light propagate in an optical fiber as guided modes for wavelength-division multiplexing (WDM) applications. Due to the phase matching provided by the input and output gratings **30**A and **30**B, the spectral content and distribution of the output light **150'** is the same as (or at least substantially the same as) the input light **150**. Thus, the AR optical system **10** is capable of color imaging.

Meanwhile, in an example, different light **250** (e.g., visible light from an object or scene, not shown) travels from the front region FR to the back region BR through the AR optical system **10** and in particular passes through the output grating **30**B in the direction perpendicular to the grating elements **32**B, i.e., in the +z direction. The light **250** is substantially undistorted by the output grating **30**B as it passes therethrough. This is because there is no phase matching provided by the output grating **30**B to the light **250**.

An advantage of utilizing a waveguide structure **100** in AR optical system **10** is that the output light **150** is emitted substantially continuously along the length of the output grating **30**B. This is in contrast to conventional light-guide-based AR systems wherein the light rays get trapped within the light guide by total-internal reflection and only emerge at discrete locations along the light guide. Continuous extraction of the output light **150'** along the output grating **30**B, as opposed to discrete extraction for a conventional light guide, results in a more uniform light distribution across the output grating (i.e., exit pupil) and thus a corresponding better augmented-image quality as observed by the user.

In an example, the input light **150** can also be substantially monochromatic for monochromatic imaging. Also in an example, the AR optical system **10** can be configured to separately handle different select wavelengths of input light

150. For example, for input light 150 having red (R), green (G) and blue (B) components, three different waveguide structures 100 can be disposed in a stacked configuration and separated using spacing layers (e.g., air or low-index films), with the different waveguide structures respectively configured to handle the R, G and B input light 150. In another example, two waveguide structures 100 can be stacked, with one waveguide structure designed to handle the R and G input light 150 while the other waveguide structure designed to handle G and B input light. Thus, a stacked configuration for an AR optical system 10 operates in essentially the same manner as the non-stacked configuration, with the different wavelengths of the input light 150 traveling in a different waveguide structure.

Example Grating Configurations

FIGS. 7A through 7D are top-down views of examples of AR optical system 10 illustrating example configurations for the input grating 30A and the output grating 30B. In the examples of FIGS. 7A and 7B, the input grating 30A has linear grating elements 32A and an overall circular shape while the output grating 30B also has linear grating elements 32B but has an overall rectangular shape. Moreover, in the example the input grating 30A has a substantially smaller area than the output grating 30B.

The output grating 30B of FIG. 7A is shown with a propagation vector K that is parallel with the x-axis while the output grating of FIG. 7B has a propagation vector in the x-y plane as defined by the angle θ.

FIG. 7C illustrates an example wherein output grating 30B has a two-dimensional configuration with crossed elements 32A and 32B that define at least two grating momentum vectors K_1 defined by θ_1 and K_2 defined by θ_2. The output grating can have additional grating propagation (momentum) vectors K_i defined by angles θ_i.

In other examples, the output grating 30B can include curved grating elements 32B, such as shown in FIG. 7D, wherein the grating elements are concentrically arranged to define a continuum of propagation vectors K.

A variety of shapes and sizes for the grating elements 32A and 32B of the input and output gratings 30A and 30B can be effectively employed, depending on the desired functionality of the AR optical system 10. Additionally, the input and/or output grating 30A and/or 30B can comprise two or more discrete grating regions with different types of grating elements 32A and/or 32B. A two-dimensional configuration for the input grating 30A and/or the output grating 30B may be effectively employed in cases where it is desirable to reduce the total area of the AR optical system 10 and to simplify the grating layout.

Curved AR Optical Systems

The AR optical systems 10 described above have a planar configuration by way of example and for ease of illustration and explanation. However, the AR optical system 10 is not so limited and can be curved, i.e., can have one or more curved surfaces.

FIG. 8 is similar to FIG. 2 and illustrates an embodiment of the AR optical system 10 having two surfaces with a convex curvature. FIG. 9 is similar to FIG. 8 and illustrates an embodiment of the AR optical system 10 having two surfaces with a concave curvature. Other examples can include just one surface of the AR optical system 10 being curved, such as the bottom-most surface as shown in FIG. 10. FIG. 11 illustrates an example wherein the AR optical system 10 includes the cap layer 50 and the top surface 52 of the cap layer is curved while the waveguide layer 40 is substantially planar.

In an example, one or more curved surfaces may be configured to provide corrective imaging. FIG. 12 illustrates an example embodiment wherein the bottom surface 24 of the substrate 20 includes a locally curved portion 24C designed to provide corrective imaging for a user 350 (see FIG. 13A, introduced and discussed below).

In addition, the AR optical system 10 can be configured with the waveguide layer 40 placed on the bottom surface 24 of the substrate 20, and the example configurations disclosed herein show the waveguide layer on the top surface of the substrate for the sake of illustration. In addition, any of the surfaces (or portions thereof) within the AR optical system 10 can be configured as a corrective surface. In examples, the AR optical system 10 can have multiple corrective surfaces. Likewise, various combinations of curvatures (e.g., convex and concave) can be employed beyond the examples shown by way of illustration in FIGS. 8 through 12.

In configurations where the waveguide structure 100 of the AR optical system 10 has a relatively strong curvature, the guided modes 120 may no longer be true bound modes but are more properly described as leaky resonant modes. Leaky resonant modes do not substantially change the operation of the waveguide structure 100, and in fact, may improve angular resolution by coupling a range of input (coupling) angles θ to each mode and opposed to discrete coupling angles to each mode.

In other examples, the grating period Λ of the input and output gratings 30A and 30B may be non-constant (e.g., chirped) to account for any curvature in the waveguide structure 100 and to maintain correct coupling angles θ for the incident light 150 as well as maintaining output angles θ' for the outputted light 150'. The grating height h of the input and output gratings may be non-constant to vary the rate at which input light 150 is coupled in the waveguide structure 100 and output light 150' is coupled out of the waveguide structure, respectively.

AR Systems

FIG. 13A is a schematic diagram of an example embodiment of an AR system 300 that includes the AR optical system 10 disclosed herein. A planar configuration of the AR optical system 10 is shown by way of example and for ease of illustration. The AR system 300 includes a display apparatus 310 optically coupled to the input grating 30A of the AR optical system 10 by a coupling optical system 320. In an example, the display apparatus 300 is a micro-display, e.g., a micro-display chip. In an example, the coupling optical system 320 comprises one or more optical elements such as lenses, mirrors, beam splitters, etc. The coupling optical system 320 can comprise micro-optical elements to minimize size and weight.

The AR system 300 is shown disposed relative to a user 350 and relative to a real object 400, which resides adjacent the front region FR of the AR optical system 10 and is shown by way of example as a tree. The real object 400 can also be considered as a scene being viewed by the user through the AR optical system 10. The display apparatus 310 is shown as providing a display image 312, which by way of example is depicted as a bird. The light 150, which constitutes display light associated with the display image 312, is directed to the input grating 30A of the AR optical system 10 over a range Δθ of input (coupling) angles θ (e.g., over an input FOV) by the coupling optical system 320. The input (display) light 150 is optically coupled into the waveguide structure 100 at the select coupling angles θ within the input FOV, as described above, to generate multiple (N) guided modes 120. The N guided modes 120 then travel within the waveguide structure 100 to the output grating 30B, with the input and output gratings **30**A and **30**B providing phase matching converts the N guided modes **120** to corresponding output light **150'** at discrete output angles θ' corresponding to the number N of the guided modes. While the output angles θ' are discrete, the output light **150'** is outcoupled substantially continuously over the length of the output grating **30**B.

The output light **150'** is directed to one or both eyes **352** of the user **350**. Likewise, one or both eyes of the user receives light **250** from the object **400** directly through the output grating **30**B (see also FIG. **6**A). The eye or eyes **352** of the user **350** thus forms an augmented image **500** on the eye's retina **354**, wherein the augmented image includes a real image **400'** of the object **400** and a virtual image **312'** of the display image **312**.

In an example, the AR system **300** can optionally include at least one corrective lens **600** operably disposed between the eye **352** of the user **350** and AR optical system **10** to provide corrective imaging, e.g., in case the user's eye has aberrations. In an example, the corrective lens **600** constitutes one or more conventional eyeglass lenses. As noted above, corrective imaging can also be provided by at least a portion of one or more of the surfaces waveguide structure **100** being curved.

FIG. **13**B is a schematic diagram of example AR eyewear **650** that incorporates the AR system **10** disclosed herein and that can be worn by the user **350**. The AR eyewear includes lenses **652** and temples **654**. In the example shown, each lens **352** includes an output grating **30**B. The input gratings **30**A reside at respective outer portions of the lenses **352**. At least a portion of each of the lenses **352** includes the waveguide structure **100** described above. The display apparatuses (e.g., micro-displays) **310** and the coupling optical systems **320** can be supported by each of the temples **654** (only one display and coupling optical system are shown for ease of illustration).

FIG. **14** is similar to FIG. **13**A and illustrates an example embodiment of the AR system **300** wherein the user **350** is replaced with an imaging optical system **700**, i.e., the imaging optical system replaces the user's eye(s) **352**. The imaging optical system **700** includes an imaging lens **702** and an image sensor **704** on which is formed the augmented image **500**. In an example, the imaging optical system **700** comprises a digital camera. In an example, the image sensor **704** is operably coupled to image processing electronics **710**, e.g. such as associated with a digital camera. In an example, the user's eye **352** constitutes an example of an imaging optical system **700**, with the user's brain performing the necessary image processing of the augmented image **500**.

It will be apparent to those skilled in the art that various modifications to the preferred embodiments of the disclosure as described herein can be made without departing from the spirit or scope of the disclosure as defined in the appended claims. Thus, the disclosure covers the modifications and variations provided they come within the scope of the appended claims and the equivalents thereto.

What is claimed is:

1. An augmented reality optical system for use in an augmented reality system at an operating wavelength, comprising:

a substrate having an index of refraction ns at the operating wavelength, a top surface and a bottom surface;

an input grating and an output grating each formed either in or on the top surface of the substrate and laterally spaced apart from each other;

a waveguide layer having a body, a top surface, a bottom surface and a thickness 1 μm≤THG≤100 μm with the bottom surface of the waveguide layer supported on the top surface of the substrate so that the input and output gratings extend into the waveguide layer, and wherein the waveguide layer has an index of refraction $n_G \geq n_S$ at the operating wavelength and supports multiple guided modes;

wherein the input and output gratings provide phase matching so that input light incident upon the input grating is coupled into the waveguide layer and travels in the guided modes to the output grating, and is coupled out of the waveguide layer by the output grating as output light.

2. The augmented reality system according to claim **1**, wherein the substrate refractive index $n_S \leq 1.5$ and the waveguide layer refractive index $n_G \geq 2$ at the operating wavelength.

3. The augmented reality system according to claim **2**, wherein the number of multiple guided modes is between 500 and 1000.

4. The augmented reality optical system according to claim **1**, wherein the waveguide layer has a thickness THG in the range 25 μm≤THG≤50 μm.

5. The augmented reality optical system according to claim **1**, wherein the waveguide layer has a thickness THG in the range 30 μm≤THG≤40 μm.

6. The augmented reality optical system according to claim **1**, wherein the waveguide layer comprises a polymer and the substrate comprises a glass.

7. The augmented reality optical system according to claim **1**, wherein the substrate comprises a glass material and wherein the waveguide comprises at least one of an oxide material and a fluoride material.

8. The augmented reality optical system according to claim **1**, wherein the substrate comprises a glass material, wherein the input and output gratings comprise a polymer, and wherein the waveguide layer comprises either an oxide material or a combination of an oxide material and a fluoride material.

9. The augmented reality optical system according to claim **1**, wherein the substrate comprises a polymer material and the waveguide layer comprises either an oxide material or a combination of an oxide material and a fluoride material.

10. The augmented reality optical system according to claim **9**, wherein the polymer material comprises a thermoplastic.

11. The augmented reality optical system according to claim **9**, wherein the waveguide layer comprises silicon.

12. The augmented reality optical system according to claim **1**, wherein the waveguide layer and the substrate are each planar.

13. The augmented reality optical system according to claim **1**, wherein at least one of the waveguide layer and the substrate has a curved surface.

14. The augmented reality optical system according to claim **1**, further comprising a cap layer disposed on the top surface of the waveguide layer, wherein the cap layer has an index of refraction $n_C < n_G$.

15. The augmented reality optical system according to claim **1**, wherein the input grating comprises linear input grating elements and wherein the output grating comprises linear output grating elements.

16. The augmented reality optical system according to claim **1**, wherein the input grating comprises two-dimensional input grating elements and wherein the output grating comprises two-dimensional output grating elements.

17. The augmented reality optical system according to claim **1**, wherein the output light has a field of view (FOV) in the range 50°≤FOV≤70°.

18. The augmented reality optical system according to claim **1**, wherein the input light is polychromatic.

19. The augmented reality optical system according to claim **1**, wherein the input light is monochromatic.

20. The augmented reality optical system according to claim **1**, wherein the substrate comprises a low-index layer that defines the substrate top surface, wherein the low-index layer has an index of refraction $n_L < n_S$.

21. An augmented reality system for viewing an object or a scene, comprising:

an augmented reality optical system having a front region and a back region, wherein the augmented reality optical system comprises:

a substrate having an index of refraction n_S at the operating wavelength, a top surface and a bottom surface,

an input grating and an output grating each formed either in or on the top surface of the substrate and laterally spaced apart from each other,

a waveguide layer having a body, a top surface, a bottom surface and a thickness 1 μm≤THG≤100 μm with the bottom surface of the waveguide layer supported on the top surface of the substrate so that the input and output gratings extend into the waveguide layer, and wherein the waveguide layer has an index of refraction $n_G \geq n_S$ at the operating wavelength and supports multiple guided modes, and

wherein the input and output gratings provide phase matching so that input light incident upon the input grating is coupled into the waveguide layer and travels in the guided modes to the output grating, and is coupled out of the waveguide layer by the output grating as output light;

a display apparatus disposed in the back region and that generates the input light; and

a coupling optical system operably arranged relative to the display apparatus and configured to direct the input light to the input grating of the augmented reality optical system over an input field of view.

22. The augmented reality system according to claim **21**, further comprising an imaging optical system operably arranged in the back region to receive the output light from the output grating over an output field of view.

23. The augmented reality system according to claim **21**, wherein light from the object or the scene is transmitted through the output grating from the front region to the back region and to the imaging optical system, and wherein the imaging optical system combines the output light and the light from the object or the scene to form an augmented image.

24. The augmented reality system according to claim **21**, where the imaging optical system comprises at least one eye of a user.

25. The augmented reality system according to claim **21**, wherein the output field of view is in the range from 50° to 70°.

26. The augmented reality system according to claim **21**, wherein the input light is polychromatic.

27. An augmented reality system, comprising:

a waveguide structure comprising a waveguide layer of refractive index n_G and a thickness THG in the range 1 μm≤THG≤100 μm, the waveguide structure supported on a substrate having a refractive index n_S, wherein $n_G - n_S \geq 0.5$, and wherein the waveguide structure supports multiple guided modes;

an input grating and an output grating that each resides within the waveguide layer, wherein the input and output gratings provide phase matching and are laterally spaced apart from one another;

a front region and a back region;

a display apparatus disposed in the back region and that generates the input light; and

a coupling optical system operably arranged relative to the display apparatus and configured to direct the input light to the input grating of the augmented reality optical system over an input field of view.

28. The augmented reality optical system according to claim **27**, wherein the waveguide layer comprises a polymer material and the substrate comprises a glass material.

29. The augmented reality optical system according to claim **27**, wherein the input and output grating are configured to operate over a visible operating wavelength band.

30. The augmented reality optical system according to claim **27**, wherein at least one of the waveguide layer and the substrate are planar.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,929,667 B2
APPLICATION NO. : 16/156355
DATED : February 23, 2021
INVENTOR(S) : John Tyler Keech et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims

In Column 11, Line 63, Claim 1, delete "ns" and insert -- n_s --, therefor.

In Column 14, Line 11, Claim 24, delete "where" and insert -- wherein --, therefor.

Signed and Sealed this
Eighth Day of August, 2023

Katherine Kelly Vidal

Katherine Kelly Vidal
Director of the United States Patent and Trademark Office